An Intercomparison of Acoustic Current Meters Deployed on the Scotian Shelf

A. Drozdowski, B.J.W. Greenan, M.D. Scotney, J.W. Loder, and Y. Geshelin

Ocean Sciences Division
Maritimes Region
Fisheries and Oceans Canada

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

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ABSTRACT

Drozdowski, A., B.J.W. Greenan, M.D. Scotney, J.W. Loder, and Y. Geshelin. 2010. An intercomparison of acoustic current meters deployed on the Scotian Shelf. Can. Tech. Rep. Hydrogr. Ocean. Sci. 264:vi + 53 pp.

A subsurface mooring was deployed on the Scotian Shelf for the period of 8 May – 3 June 2008 for the purpose of doing an intercomparison of two new acoustic Doppler single-point current meters: the Aanderaa Seaguard and Teledyne RDI Doppler Volume Sampler (DVS). These were compared with both a mechanical current meter (Aanderaa RCM8) and an upward looking Teledyne RDI acoustic Doppler current profiler (ADCP).

An intercomparison of five current meters indicates that all instruments provide a good measure of speed and direction in a shelf environment with moderate flows, with correlation coefficients for each of speed and direction exceeding 0.96 in all cases. Vertical shear in this environment was determined to be a significant source of differences across the 11 m of the water column where the current meters were deployed. It was found that all instruments had high directional differences at low speeds (< 10 cm s^{-1}). For speeds less than 5 cm s^{-1}, the RMS difference was between 20-45 degrees. The DVS appears to slightly underestimate the daily displacement by approximately 5-10%. This may be partially attributable to errors in direction from the heading/pitch/roll sensor, which has been subsequently replaced by the manufacturer with a new sensor design in 2009.

It was found that occasionally very large differences occur between instruments (in excess of 6 cm s^{-1} and 75 degrees). Discrepancies of this magnitude were shown to be of low probability (0.1 % of the time for the speed and 0.5 % for the direction) but several orders of magnitude higher then can be expected from a normal distribution made to fit the data. The source of these extreme differences appears linked to internal wave activity at the mooring site.

RÉSUMÉ

Drozdowski, A., B.J.W. Greenan, M.D. Scotney, J.W. Loder, and Y. Geshelin. 2010. An intercomparison of acoustic current meters deployed on the Scotian Shelf. Can. Tech. Rep. Hydrogr. Ocean. Sci. 264:vi + 53 pp.

Un corps mort sous-marin a été déployé sur la plate-forme Scotian pour la période du 8 mai au 3 juin 2008 aux fins d'une comparaison réciproque de deux nouveaux courantomètres à point unique à effet Doppler acoustique : l'Aanderaa Seaguard et le Doppler Volume Sampler (DVS) de Teledyne RDI. Ces instruments ont été comparés à un courantomètre mécanique (Aanderaa RCM8) et à un profileur de courant à effet Doppler acoustique (PCDA) à vision vers le haut de Teledyne RDI.

Une comparaison réciproque de cinq courantomètres montre que tous les instruments donnent une bonne mesure de la vitesse et de la direction dans le milieu d'une plate-forme où les écoulements sont modérés, les coefficients de corrélation de la vitesse et de la direction dépassant 0,96 dans tous les cas. On a déterminé que le cisaillement vertical dans ce milieu est une source importante de différences dans les 11 m de la colonne d'eau où les courantomètres ont été déployés. On a trouvé que tous les instruments présentaient de fortes différences de direction à de faibles vitesses (< 10 cm s^{-1}). Dans le cas des vitesses inférieures à 5 cm s^{-1}, la différence efficace était de 20 à 45°. Le DVS a semblé sous-estimer légèrement le déplacement quotidien d'environ 5 à 10 %, ce qui peut être partiellement attribuable à des erreurs de direction en provenance du capteur de cap/tangage/roulis, capteur que le fabricant a par la suite (en 2009) remplacé par un capteur d'une nouvelle conception.

On a trouvé qu'à l'occasion, il y a de très grandes différences entre les instruments (de plus de 6 cm s^{-1} et de 75°). On a montré que des différences de cette ampleur sont d'une faible probabilité (0,1 % du temps pour la vitesse et 0,5 % du temps pour la direction), mais on peut alors s'attendre à plusieurs ordres d'ampleur supérieure à partir d'une répartition normale pour correspondre aux données. La source de ces différences extrêmes semble être liée à l'activité interne des vagues au mouillage.

1. INTRODUCTION

Over the last two decades, mechanical current meters have gradually ceded their dominance in the field of oceanography to newly-developed acoustic instruments, most of which use Doppler-shifted acoustic backscatter to estimate water velocity. Reasons for the slow transition to acoustic current meters include the higher cost of these new new instruments, the tendency to adhere to proven technology until a better one is clearly demonstrated, and the difficulty of comparing moored measurements using different technologies. In the field of oceanography, long time series are critical for the analysis of trends on decadal and longer time scales; therefore, it is important to be able to combine measurements made with different instruments. Even measurements made with the same types of current meters have shown discrepancies due to differences in mooring design (e.g. Hamilton et al. 1997).

Acoustic current meters offer several significant advantages over mechanical systems. Due to the absence of mechanical parts they are less sensitive to biological fouling and have lower maintenance requirements. They also have more flexibility in sampling strategies and are better suited to low-current environments where mechanical rotor stalling can bias measurements. In addition, the older generation current meters required significant effort to calibrate the compass which has been eliminated in the modern acoustic instruments.

There are two types of acoustic measurements: point sensing (includes both Doppler shift and travel-time difference technologies) and profiling (Dopper shift of binned acoustic backscatter). The advent of acoustic profilers has enabled current measurements covering several hundred meters of the water column. It is now commonplace to deploy acoustic profilers to acquire full water column measurements on the continental shelf and near-shore areas, and to obtain higher resolution of vertical structure in parts of the water column in the deep ocean. However, in the deep ocean, point sensing current meters remain in common use.

Within the last decade, several studies have been carried out to evaluate the performance of the new generation of acoustic current meters. Gilboy et al. (2000) carried out a field test at the Bermuda Testbed Mooring in which they compared a Vector Measuring Current Meter (VMCM) (Weller and Davis, 1980) with an RDI Acoustic Doppler Current Profiler (ADCP) and a Falmouth Scientific Acoustic Current Meter (ACM). The ACM is an acoustic travel-time point sensor which samples at 2 Hz. Analyses of subtidal measurements indicated that the ACM mean for the entire experiment was 1.5 cm s^{-1} (2.5 cm s^{-1}) smaller than that of the VMCM (ADCP bin at the same depth). The correlation of velocity components from instrument pairs was at least 0.95 in all cases. The major limiting factor of the field test was a directional error/bias in the ACM which created offsets of 20°-30°.

More recently, Hogg and Frye (2007) evaluated the performance of three acoustic Doppler current meters (Aanderaa RCM11, Nortek Aquadopp, Sontek Argonaut) and two acoustic travel-time current meters (Nobska MAVS, Falmouth Scientific ACM). The results from the acoustic instruments were compared to two well-documented mechanical current meters, the VMCM and the Vector Averaging Current Meter (VACM; McCullough, 1975). Two procedures were used to evaluate the performance of the instruments: first, the current meters were placed close to each other on deep-sea moorings southeast of Bermuda; second, the instruments were mounted on a CTD system and lowered through the water column in an attempt to calibrate the current meters. The moored tests indicated that the RCM11 speeds

appeared to have a small, but systematic, bias relative to those of the VMCM and VACM for the measured speed range of up to 15 cm s^{-1}, resulting in a 10%-25% reduction in RCM11 speed. However, a low RCM11 bias was not apparent in the noisier comparison of the CTD-lowered instruments for speeds of about 25 cm s^{-1}, so the conclusions regarding the RCM11 speeds seem somewhat equivocal. Both the first-generation Aquadopp and Argonaut current meters displayed biases due to low signal-to-noise ratios in deep subthermocline waters which were low in scatterers. However, a subsequent version of the Aquadopp reduced this bias significantly. The travel-time instruments were hampered by technical issues but, when they were operating, they appeared to be capable of making measurements within 1-2 cm s^{-1} of the reference instruments.

In addition to these deep-ocean comparisons, Pettigrew et al. (2005) carried out field tests in a protected coastal embayment over a 30-day period. They compared a bottom-mounted Aanderaa RDCP600 Doppler profiler to a string of seven moored Aanderaa RCM9 MKII single-point Doppler current meters, and an RDI 600 kHz Workhorse ADCP. Results of vector correlations and difference statistics showed good agreement among all of the instruments. Mean differences were generally less than 0.5 cm s^{-1} and the root-mean-squared (RMS) differences were on the order of 2 cm s^{-1}.

The Bedford Institute of Oceanography (BIO) has deployed a number of moorings over the decades to assess the performance of various current meters. The primary goal of this report is to describe the results of a 2008 current meter mooring deployment designed to intercompare two new single-point acoustic current meters with more commonly-used ones. The new instruments were the Aanderaa Seaguard Recording Current Meter (Seaguard RCM; http://www.aadi.no/Aanderaa/Products/Seaguard/default.aspx) and the Teledyne RDI Doppler Volume Sampler (DVS; http://www.rdinstruments.com/dvs.aspx). The other instruments deployed on the mooring were an Aanderaa RCM8 mechanical (paddle-wheel rotor) current meter, an Aanderaa RCM11 acoustic current meter, a second Seaguard RCM, and a 300-kHz Teledyne RDI ADCP. The report will also draw on data from two previous BIO moorings in the Scotian Shelf region to compare the RCM8 and RCM11 rates.

A sub-goal of the 2008 deployment was to critically assess the current speed measurements among the RCM8, RCM11 and Teledyne RDI ADCP which have been the primary current meters used at the Bedford Institute of Oceanography (BIO) over the past three decades. In addition to the possible RCM11 rate underestimation indicated by Hogg and Frye (2007), there has been some uncertainty regarding the appropriate rotor-count-to-speed calibration for the paddle-wheel RCMs. Tow tank tests carried out by the UK Centre for Environment, Fisheries and Aquaculture Sciences (CEFAS) in 1999-2000 (J. Read and K. Medler, unpublished report 2001) indicated that the use of the manufacturer's calibration formula was resulting in overestimation of current speed by 10%. Earlier *in situ* comparisons by BIO (Loder and Hamilton, 1990) of RCM8 speeds with those from an Ametek Straza Vessel-Mounted ADCP and an Interocean S4 electromagnetic current meter had indicated that the average value (over a tidal period) of the ratio of RCM8 speed to ADCP (or S4) speed for current speeds in the range of 0.4 to 1.2 m s^{-1} ranged from 0.98 to 1.07 (depending on the mooring and location), with a mean of 1.03. Because of the variability across deployments in these estimates, and hence the uncertainty in the most appropriate *in situ* calibration coefficients, BIO has continued to use the manufacturer's formula (but with some ongoing uncertainty regarding the accuracy of the RCM8 measurements). Recent RCM8 measurements at BIO have also indicated an apparent variable threshold and possible stop-start dependence for rotor stalling in weak

currents, for some instruments and deployments. This issue will be only briefly discussed here, but examined in more detail in a separate report.

Section 2 of this report will explain the methods used in this study including mooring design and current meter descriptions. The results obtained from the mooring deployed in 2008 will be illustrated in Section 3 and will be followed by a discussion and analysis in Section 4. The conclusions of this study will be presented in Section 5.

2. METHODS

a. Mooring Design

The 2008 intercomparison of current meters was carried out by placing closely-spaced instruments on a taut mooring (BIO Consecutive Mooring No. 1681, Figure 1). A detailed summary of each instrument deployed is provided in Table 1. While the sampling strategy employed varied among instruments due to their inherent designs, all current meters provided estimates of velocity at a 10 minute recording interval. Streamlined buoyancy packages were used to minimize mooring-related vibrations as well as for mounting the RDI ADCP.

The primary purpose of deploying this mooring was to evaluate the performance of the two new acoustic Doppler current meters: the Aanderaa Seaguard RCM and the Teledyne RDI DVS. The Seaguard employs the Aanderaa ZPulse™ technology, which transmits an acoustic pulse of several distinct frequencies to improve the data quality of the Doppler current measurements without increasing the power drain, measurement time, or pulse length (Jakobsen et al., 2008). Seaguard #33 (SG33) at 63 m (below the surface) was set up for burst mode sampling (300 pings in the last 60 seconds or recording interval) while Seaguard #20 (SG20) at 72 m used spread mode (300 pings evenly spaced over the recording interval), to compare the performance of these methods on otherwise identical current meters. SG33 at the top of the mooring was mounted 3 m above the DVS to minimize interference with the upward-looking acoustic beams of this current meter.

The DVS was implemented in a four-beam Janus configuration which provides five bins of velocity data with a range up to 5 m. A high sample-rate compass/tilt sensor enables the user to estimate the relative importance of mooring vibrations. Each ensemble collected during this deployment was comprised of about 280 individual acoustic pings; the exact number of pings can vary slightly between ensembles as it depends on how long it takes for the instrument to sample all its sensors. The DVS functioned in spread mode.

The other three current meters deployed on the 2008 mooring were ones with which we have substantial field experience. The Aanderaa RCM8 mechanical current meter was the only instrument in the deployment that did not utilize an acoustic technique. After decades of use, the strengths and weaknesses of this type of current meter are generally well known. The primary issues with the use of the RCM8 at BIO have been the exact rate calibration formula, the tendency of the paddle-wheel rotor to stall at low flow speeds, and the underestimation of rate due to rotor shielding in the presence of strong mooring vibration (Loder and Hamilton, 1990). The RCM8 was mounted in-line on the 2008 mooring at 74 m with a Sea-Bird 37M MicroCAT temperature and conductivity sensor just below. The Aanderaa RCM11 acoustic meter, which has been utilized by BIO as a replacement for the RCM8, was mounted in-line on the mooring 1 m below the DVS. Its performance has been evaluated by Hogg and Frye (2007), and it has been

intercompared with the RCM8 (1-m in-line spacing) in three previous BIO mooring deployments, two of which were in a continental shelf environment: one in spring 2007 at the same site as the present deployment, and the other in 2003 in Laurentian Channel. Further background on these deployments is provided in Appendix A.

Finally, a 300-kHz Teledyne RDI ADCP was moored inline in a streamlined buoyancy float at 112 m on the 2008 mooring in an upward-looking configuration. The ADCP acquired 80-ping ensembles in a 4-minute burst mode at a 10-minute sampling interval. Vertical resolution was 4 m and covered the entire water column above the ADCP.

b. Deployment Summary

The 2008 mooring was deployed at Station 2 on the Halifax Line (henceforth HL2) on the Scotian Shelf (Figure 2) for the period of 8 May – 3 June 2008 in a water depth of 155 m. Previous moored measurements (e.g. Lively 1988) in this region in winter indicate mean (maximum) speeds at mid-depths ranging from 15 (37) cm s^{-1} on the 100-m isobath to 24 (74) cm s^{-1} on the 170-m isobath, with significant contributions from weak mixed diurnal-semidiurnal tidal currents with amplitudes up to 4 cm s^{-1} for individual constituents, local and larger-scale wind forcing, and the seasonally-varying Nova Scotian Current (Anderson and Smith 1989).

In the 2008 mooring, pressure records from instruments indicated that current meters located in the upper group (SG33, DVS, RCM11, see Figure 1) had a possible issue of wire entanglement for the period of 8 - 12 May. It appears that the streamlined Viny float, which was designed to be at the top of the mooring, was somehow caught in the DVS structure; this would most likely have happened while the mooring was deployed as our standard procedure involves laying out the mooring on the surface prior to release of the anchor. The streamlined float was freed without intervention on 12 May 2008 and ascended to its designed depth. For this reason, analysis of data from this mooring only used data from 12 May onward.

All instruments on the mooring returned complete data records for the entire period of the mooring deployment. During the initial processing of the RCM11 data, it was noted that its speed and direction values were significantly different from those of nearby instruments. The heading remained within a few tens of degrees of True North throughout the deployment. This instrument was returned to Aanderaa for investigation, but nothing conclusive was found to explain the malfunction of the RCM11. Therefore, this instrument has been excluded from the analysis in this report. The 2003 LC1 and 2007 HL2 RCM8 vs RCM11 comparisons are included in Appendix A to help fill the gap created by this malfunction. The deployment at LC1 (Figure A2) indicated there was a strong correlation ($r = 0.98$ for rate, $r = 0.86$ for direction) between the RCM8 and RCM11. The slope of the best fit for rate (direction) indicate that the RCM8 is +10% (-8%) of that for the RCM11. For the 2007 HL2 mooring (Figure A4), the correlation is slightly higher for both rate and direction. The slope and intercept of the best fit for direction is nearly identical to that observed at LC1. However, the slope of the best fit for rate of RCM8 vs. RCM11 is 0.95, which is 15% different from the LC1 mooring result. The reason for this difference is unexplained at this point.

The four working acoustic instruments on the 2008 mooring all returned reliable data as reported by the various quality control parameters of each instrument. The ADCP reported mean percent good pings of 99.91% and 1.36% standard deviation for the 21 bins below 20 m The top Seaguard (SG33) reported a mean signal strength of -35.8 dB with standard deviation of 3.35 dB. The bottom Seaguard (SG20) had similar numbers of -35.7 dB and 3.0 dB. The instrument manufacturer reports a noise floor of about -71 dB which suggests a high signal-to-noise ratio

(SNR) for both data sets. The DVS provided good-quality data from the lower three bins. The best bin (at 1 m), reported a mean of 100% good pings with 0% std. However, it should be noted that RDI's standard for differentiating signal from noise is to declare a good ping if more than 64 counts are recorded on the A/D converter. The second bin (2 m), reported 85.6% good pings with std of 29.6%. The overlapping good data from both bins was compared and found to correlate highly (99% correlation and R^2=0.99) for both speed and direction. The 3rd bin (3 m) returned only 3.3% good pings. The likely cause of this low data return is interference with the instrument directly above (SG33). Only the data from the 1 m bin was used in this investigation.

3. RESULTS

Figure 3 - Figure 5 show time series of the speed, direction and temperature data recovered from each instrument on the 2008 mooring. A compass correction for magnetic declination (-18.53 degrees) was applied to all instruments. The time series indicate a good overall qualitative agreement between all of the instruments, but intermittent periods with notable discrepancies in one or both of speed and direction.

Table 2 summarizes the current statistics for each instrument. For the ADCP, only the results from the bins closest to the single point current meters are presented: bin 9 at 70m near SG20, bin 10 at 66m near the DVS and bin 11 at 62m near SG33. The magnitude (7.1-8.7 cm s^{-1}) and direction (235-240° T) of the mean velocity show differences of up to 20% across instruments but are in a range consistent with the climatology of the Nova Scotia current in this region (Anderson and Smith, 1989). Some of the differences in mean current magnitude can be attributed to shear in the water column as observed with the ADCP profiler (bins 8-11), but it can only account for approximately 0.9 cm s^{-1}. The standard deviation of the current speed is moderate ranging from 10.2 to 10.8 (cm s^{-1}). Peak speed of 34-40 cm s^{-1} is also moderate for a continental shelf location. An overview of the flow is summarized with a progressive vector diagram (Figure 6), which indicates that the DVS magnitude is underestimated over the 3-week period of the deployment. A closer examination of the results is provided in daily PVD plots in Appendix C as well as in Tables C1 and C2. These plots, along with detailed examination of the time series of current direction (not shown), show that the DVS heading was as much as 15 deg different from the nearest ADCP bin and the SG33 for extended periods of time. This does not seem to be a systematic error for which a post-deployment correction could be applied. The calibration of the sensor was carried out prior to the mooring deployment and passed the control checks in the instrument configuration software. However, this required significant effort of the technician to complete, which may cast some doubt on the reliability of this process. In the fall of 2009, the heading/pitch/roll sensor in new DVS instruments was replaced by a new sensor.

Figure 7 shows the distribution of the measured speed binned in 5 cm s^{-1} intervals. All instruments provide comparable results with the most noticeable differences being the SG20 showing fewer samples below 5 cm s^{-1} and more samples in the 15-20 cm s^{-1} range. The former difference can be attributed to the instrument working in spread mode, and hence averaging out the short lived low speed events. But the latter difference is puzzling. Overall, approximately 75% of the data samples were observed to be in the 5-20 cm s^{-1} range and about 15% of measurements are below 5 cm s^{-1}. Moderate current speeds (> 20 cm s^{-1}) occur only 10% of the time.

A plot of the low speed distribution (< 5 cm s^{-1}) from the current meters (Figure 8) indicates that speeds below 1 cm s^{-1} comprise less than 1% of the measurements, with the actual

percentage ranging from 0.7-0.8% for the DVS and ADCP-bin10 to only 0.2-0.3% for the deeper SG20 and ADCP-bin8. The SG33 appears to be anomalous here in that, although it is the shallowest meter, its percentage occurrence below 1% is closer to those of the lower pair of other acoustic meters. The RCM8 shows no speeds below 1 cm s^{-1}, consistent with the value of 1.1 cm s^{-1} assigned to zero rotor counts in the manufacturer's original calibration formula. On the other hand, the RCM8 shows a higher cumulative fraction of low speeds (by about 2%) than the other instruments for speeds up to the range of 1.1 to about 5 cm s^{-1}. This suggests that rotor stalling (or under-speeding) is occurring for low speeds in the range 1.1-5 cm s^{-1} for about an additional 1% of the time (beyond the 1% with actual speeds below 1 cm s^{-1}). Since the cumulative fractions of low speed for the RCM8 and nearby instruments agree at a speed of about 5 cm s^{-1}, it appears that the rotor stalling or under-speeding is only occurring for speeds up to this magnitude.

Figure 9 shows the cumulative spectral energy from the six instruments. The choice of variance for units provides a convenient absolute energy scale which can be validated against the total variance (std^2) of each instrument. Approximately 70 % of the variance resides in the 0.7 and 2.0 cycles day^{-1} range. This band includes diurnal and semi-diurnal tides and inertial oscillations.

Only about 1% of the total variance resides in the frequency range greater than 2.0 cycles day^{-1}. The power density spectrum (Figure 10) provides a closer look at the high frequencies. The differences in this band could be associated with instrument uncertainties and/or different instrument responses internal waves, but they will be referred to here as noise. The ADCP has the highest amount of noise. This is consistent with it having the highest reported instrument uncertainty (discussed below) and operating in burst mode (instruments that operate in spread mode average out some of the noise). The ADCP and SG33 both operated in burst modes and have the highest noise level of the group. The SG20, DVS28 and RCM8 have a slightly lower noise level, which is consistent with its spread sampling mode. Technically, the RCM8 does not function in spread mode. Velocity estimates at 12-second intervals are computed from the total number of rotor revolutions and an instantaneous direction, prior to internal vector averaging to the 10-min recording interval. The RCM8 method is more analogous to the spread mode for the acoustic measurements, but is free from acoustic noise which is present in the other instruments.

4. DISCUSSION

For the purposes of comparison, the instruments are divided into two groups according to vertical placement on the mooring line. Group1 includes the SG33 and DVS along with their corresponding ADCP bins (63 and 66 m). Group 2 contains the SG20 and RCM8 as well as their corresponding ADCP bins (72 and 74 m). The advantage of this grouping is that the instruments in each group are only 2-3 m apart, minimizing the effects of vertical shear. Each group has 4 pairings, instrument A with B, A with ADCP at depth of A, B with ADCP at depth of B and ADCP at depth of A with ADCP at depth of B. The last pair is essentially a comparison of adjacent ADCP bins. It should capture the affects of shear across the group as well as some differences related to instrument uncertainty. The instrument uncertainty in this however, should be minimized by the fact that we are comparing an instrument to itself and hence phasing out any additional differences due to differing technology, mounting and manufacturing. This comparison pair can be viewed as a baseline. All time series in the analysis were synchronized to the clock from the ADCP with linear interpolation to provide a total sample size of 3155.

Figure 11-Figure 14 show the scatter plots and best-fit lines for instruments from Groups 1 and 2. The regression statistics are summarized in Table 3. There is good agreement with correlations of 0.96-0.99 and least square coefficients of determination (R^2) of 0.91-0.98 for all pairs in both groups for both speed and direction.

Of all the speed pairs, the agreement between the SG33 and DVS is the highest (corr. = 0.99, R^2 = 0.98). The poorest agreement in speed is between the RCM8 and ADCP (corr. = 0.97, R^2 = 0.91). However, the RCM8 pairing with SG20 (corr. = 0.97, R^2 = 0.95) is on par with other instruments. It should be noted however, that these differences between instrument pairs are not statistically significant enough to draw any definite conclusions.

In terms of current direction, the highest agreement (corr. = 0.99, R^2 = 0.97) is between ADCP data spanning the vertical range (2m) in Group 2. The pairing of the SG33 and DVS also demonstrates very good correlation (corr. =0.99, R^2 = 0.95). As in the speed pairings, the poorest agreement is between the RCM8 and ADCP (corr. = 0.96, R^2 = 0.92). However, this is still a very high correlation and the agreement for the RCM8 pairing with SG20 (corr. = 0.97, R^2 = 0.95) is on par with the others.

To compare the differences in concurrent point observations rather then the absolute values themselves, the mean and root mean (RMS) differences have been computed. The mean difference is a measure of bias while the RMS is a measure of the overall agreement between two instruments (including both bias and scatter). If we compare two instruments, A and B, each with expected RMS error d_A and d_B, the expected RMS difference (d_{AB}) due to instrument uncertainty should be $(d_A^2 + d_B^2)^{0.5}$. This calculation assumes that the same volume of space is being sampled by both instruments, an assumption least valid for comparisons between the point-source current meters and the ADCP. Table 4 gives the expected measurement uncertainties for each instrument.

Table 5 shows the mean, RMS and expected differences computed for instrument pairs discussed above. A third group was created to look at the difference between the top (SG33) and bottom (RCM8) single point instruments along with the corresponding ADCP data. The purpose of this group is to examine the effects of shear across the whole 11m vertical range of the 4 instruments.

In Group 1, the mean differences are all ranging between 0.1 and 0.8 cm s^{-1} and the direction between -1.8 and 3.2 deg. The RMS differences range from 1.2 to 1.5 cm s^{-1} and 13.2 to 17.0 deg. The RMS differences indicate that the SG33 and DVS agree slightly better with each other than with the ADCP which may be attributable to the differences in sampling volume. RMS differences for all instrument pairings are larger than the predicted differences based on instrument uncertainties (d_{AB}), ranging from 1.2 to 2.7 times higher.

The mean differences are again small in Group 2, ranging between -0.2 and 0.9 cm s^{-1} and -0.7 and 5.4 deg. The RMS differences vary from 1.0 to 1.6 cm s^{-1} and 9.1 to 19.6 deg. While the rate comparisons involving the RCM8 are comparable to those for the other pairings, there is a 5 degree bias in direction in the pairings involving the RCM8

The mean differences in Group 3 are comparable to Groups 1 and 2. However, the RMS differences between top and bottom instruments are much larger (3-3.6 cm s^{-1}) for speed and 25-30 deg for direction). The total RMS difference can be expressed as, $RMS_{Tot}^2 = RMS_{Shear}^2 + RMS_{Inst}^2$, where RMS_{Shear} is the RMS difference attributable to vertical shear in the water column and RMS_{Inst} is the portion due to instrument uncertainty. From Group 3, we have two estimates for RMS_{Tot}, as quoted above for the 11 m separation (an average value of 3.3 and 27.5 deg will be used). Based on all the comparisons in Group 1 and 2, it can be seen that only about

1.5 cm s^{-1} and 18 degrees is attributable to instrument uncertainty. This leaves about $(3.3^2 - 1.5^2)^{0.5} = 2.9$ cm s^{-1} and $(27.5^2-18^2)^{0.5} = 20.8$ degrees which can be attributed to vertical shear in the water column. Expressed another way it is about 0.27 cm s^{-1} and 1.9 deg per meter. Taking the upper and lower bounds for RMS_{Tot} and RMS_{Inst} , yields an error estimate on the vertical shear calculation of plus or minus 0.04 cm s^{-1} and 0.6 deg (Table 6). It should be noted that in this calculation the estimate for RMS_{Inst} is already affected by shear; however, this is overshadowed by the dominance of the larger RMS_{Tot}^2 term.

The affect of vertical shear in Group 1 and 2 is small but not negligible. Based on the above calculation, it is about 0.8 cm s^{-1} and 5.7 deg for Group 1 and 0.5 cm s^{-1} and 3.8 deg for Group 2 based on their 3 m and 2 m vertical span. The vertical shear can be removed from each group using the formula $RMS_{Inst}^2 = RMS_{Tot}^2 - RMS_{Shear}^2$. The details are not shown here but it translates to a 15% reduction for speed RMS differences in Group 1 and 6.5 % for Group 2. The directional corrections are not as high at 5 % from Group 1 and 2 % for Group 2. The speed corrections put some of the instruments in Group 1 within the expected instrument error.

Figure 15 -Figure 18 show the distribution of mean (bias) and RMS differences as a function of current speed and direction for Groups 1 and 2. This was done with 5 cm s^{-1} bins for speed and 45 deg bins for direction. For speed, the magnitude of the biases is generally < 1 cm s^{-1} for all pairs and the RMS differences are < 2 cm s^{-1}. There are indications of small changes in the biases and RMS differences with speed and direction for some pairs, but it is difficult to draw conclusions on the significance and origin of these changes.

One consistent feature for all pairs in both groups (except for the small direction biases for ADCP pairs) is the relatively high discrepancy in direction at low speeds (<10 cm s^{-1}) The RMS directional differences where as high as 45 deg. The typical trend for these instruments is for better directional agreement at higher speeds, with the biases limited to a few degrees and the RMS differences less than 10 deg. At speeds below 5 cm s^{-1}, the largest RMS discrepancies in direction are for the pairs involving the RCM8 but those for most other pairs are also very large. There is also a persistent small bias between the RCM8 and ADCP directions at all speeds (Figure 17), which is consistent with the overall bias between the RCM8 and other instruments noted previously. Furthermore, there is a suggestion of a small increase in directional bias for speeds above 30 cm s^{-1} for most instruments.

Additionally, for direction, there are indications of changes in the bias and RMS difference by as much as 20 deg with direction for some pairs, with the largest bias changes associated with the DVS in the upper group and the RCM8 in the lower group. The largest RMS difference was in the Seaguard versus ADCP in Group 1 and RCM8 versus ADCP in Group 2. There is also a peak in RMS difference in the 45-180 deg. T. range across all instruments (except the two ADCP bins in the upper group), which may reflect a real increase in current direction variability for currents in the east, southeast and south octants.

A concluding investigation of instrument differences was made by pooling all pair differences in Group 1 and 2. The motivation here is to examine the nature of instrument error, not to look for actual differences between instruments in this intercomparison (which was done above). From the pooled data, a mean and standard deviation were computed and used to generate a normal distribution fit to the data. The absolute values of both data sets were taken and then sorted from largest to smallest and assigned a rank between 0 and 1 (largest absolute difference received 0, smallest 1). Figure 19 shows the rank plotted on the vertical axis as a function of speed and direction. The rank can be interpreted as an exceedance probability or

fraction of data above a certain speed. The vertical axis was plotted on a log scale to focus on the low-probability/ high-differences region.

One of the key results of this analysis is that 98 % of the speed differences are less than 3 cm s^{-1} and agree well with the normal distribution fit to the data. However, directional differences do not agree well for even small differences. This is attributable to extreme events that lead the standard deviation to create a broad normal distribution, which overestimates low difference events and yet significantly underestimates extreme events. Extreme outliers for speed are much more extreme than what would be expected from a normal distribution. For example, the probability of exceeding 4.5 cm s^{-1} is 10 times higher and of exceeding 5.5 cm s^{-1} is 100 times higher. Values above 6 cm s^{-1} are virtually nonexistent in the normal distribution while instruments reported differences as high as 13 cm s^{-1}. For direction, differences greater than 55 (65) degrees are 10 (100) times are more common than expected from the normal distribution. As well, the instruments report about 0.5 % of the differences above 75 degrees, while the normal distribution is virtually zero.

It is not clear what is causing this "fat tail" for the extreme outliers in both the speed and directional distribution, however as is seen in Appendix B the large differences occur during events which strongly affect the temperature structure of the water column. This indicates that internal wave activity at this mooring site could be partly responsible for the large differences observed. A separate analysis for individual instruments revealed no major differences (i.e. the extreme outliers occur in all instrument pairs). If we define extreme events as those which are ten times more common than the normal distribution, these have 0.002 probability of occurrence for speed and 0.01 for the direction. The conclusion is that extreme events are five times more common for directional measurements than for speed. Further investigation is needed to understand these occurrences and the role played by instrument errors versus ocean dynamics. Such an investigation is beyond the scope of this report. Appendix B includes some examples of these extreme differences.

5. CONCLUSIONS

An intercomparison of five current meters from a three week mooring deployment indicates that all instruments provide a good measure of speed and direction in a shelf environment with moderate flows, with correlation coefficients for each of speed and direction exceeding 0.96 in all cases. Vertical shear has been determined to be a significant source of differences across the 11 m of the water column where they were deployed. For this reason, the comparison was confined to instruments close together on the mooring line where the shear is small but not negligible.

The correlations and difference statistics for the various instrument pairs indicate that the SG33 and DVS measurements are in slightly better overall agreement than most of the other pairs, but the DVS magnitude of the mean current is underestimated by ~10%. This may be attributable to errors in the heading/pitch/roll sensor which has been replaced in the DVS by a new sensor in 2009. The values of about 1.2 cm s^{-1} and 13.7 deg for the RMS differences are somewhat higher than the expected combined instrument uncertainty of 0.45 cm s^{-1} and 7.1 deg. However, it should be noted that these instruments were sampling different water volumes in a dynamic environment. Most other instrument differences are comparable to the results of the SG33 and DVS. The poorest agreement is between the RCM8 and ADCP with a 1.6 cm s^{-1} and

19.6 deg RMS difference. The RCM8 seems to have a slight directional offset of 5 degrees on average

It was observed that all instruments had high directional differences at low speeds (< 10 cm s^{-1}). For speeds less than 5 cm s^{-1}, the RMS difference was between 20-45 degrees. The RCM8 was on the higher end of this as can be expected from its paddle-wheel and vane design. For the acoustic instruments, explaining this discrepancy is not as straightforward. It is possible that the directional reading would be underperforming at very low speeds (< 5 cm s^{-1}) since a non zero speed is need to calculate direction, but in this case the disagreement can be seen even in the 5-10 cm s^{-1} range.

It was found that occasionally very large differences occur between instruments (in excess of 6 cm s^{-1} and 75 degrees). No single instrument stood out as being the cause of this and the analysis was done by grouping all instrument pairs. Discrepancies of this magnitude were shown to be of low probability (0.1 % of the time for the speed and 0.5 % for the direction) but several orders of magnitude higher then can be expected from a normal distribution made to fit the data. The source of these extreme differences appears linked to internal wave activity at the mooring site. It is important to note that the extreme outliers are rare and were shown to have no significant affect on the overall quality of the measurement. It does however put in doubt the validity of individual point measurements since such large errors are possible. It also emphasizes the importance of filtering and time averaging data.

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TABLES

Table 1: List of instruments deployed on the comparison mooring at HL2 in May 2008.

Instrument	Manufacturer	Type	Depth	Parameters/Sampling Strategy	Data Available
Seaguard (Serial #: 33)	Aanderaa	ZPulse™ multi-frequency Doppler Current Sensor	63 m	Horizontal velocity Sampling Interval: 10 min Burst Mode Ping Count: 300 ZPulse: Yes Forward Ping: Yes Cell Size: 1.5 m	Yes
Doppler Volume Sensor (DVS, Serial #: 8928)	Teledyne RDI	2400 kHz, four-beam, Janus configuration, broad band Doppler sensor	66 m	Horizontal and vertical velocity # Bins: 5 Bin Size: 1 m Burst Mode Sampling Interval: 10 min Ping Count: ~280	Yes
RCM11 (Serial # 265)	Aanderaa	2000 kHz narrow band Doppler current sensor	67 m	Horizontal velocity Sampling Interval: 10 min Burst Mode Ping Count: 600	Yes, but problem with speed and direction
Seaguard (Serial #: 20)	Aanderaa	ZPulse™ multi-frequency Doppler Current Sensor	72 m	Horizontal velocity Sampling Interval: 10 min Spread Mode Ping Count: 300 ZPulse: Yes Forward Ping: Yes Cell Size: 1.5 m	Yes
RCM8 (Serial # 5574)	Aanderaa	Mechanical, paddle-wheel rotor	74 m	Horizontal velocity Sampling Interval: 10 min Spread Mode	Yes

SBE 37 M MicroCAT (Serial # 5435)	Sea-Bird Electronics	Moored CT sensor	75 m	Temperature, conductivity and depth Sampling Interval: 2 min	Yes
Workhorse ADCP (Serial # 8599)	Teledyne RDI	300 kHz Doppler profiler	112 m	Horizontal and vertical velocity # Bins: 30 Bin Size: 4 m Ensemble Interval: 10 min 4-min Burst Mode Ping Count: 80	Yes

Table 2: Instrument summary statistics for the deployment period of 12 May – 3 June 2008.

	ADCP Bin 11 61.7 m	SG33 63 m	ADCP Bin 10 65.7 m	DVS28 66 m	ADCP Bin 9 69.7	SG20 72 m	ADCP Bin 8 73.7 m	RCM8 74 m
Mean u ($cm\ s^{-1}$)	-7.3	-7.2	-7.0	-6.2	-6.8	-7.1	-6.5	-6.6
Mean v ($cm\ s^{-1}$)	-4.7	-4.5	-4.4	-3.5	-4.2	-4.4	-3.9	-4.7
Mag. of Mean Current ($cm\ s^{-1}$)	8.7	8.5	8.3	7.1	8.0	8.4	7.6	8.1
Dir of Mean Current Deg. T.	237.0	238.0	238.2	240.3	238.4	237.8	238.8	234.7
Max Speed ($cm\ s^{-1}$)	35.0	34.8	37.5	35.7	40.2	38.9	40.4	39.5
Min Speed ($cm\ s^{-1}$)	0.2	0.4	0	0.2	0.1	0.2	0.1	1.1
STD ($cm\ s^{-1}$)	10.7	10.5	10.5	10.5	10.3	10.6	10.4	10.2

Table 3: Regression Statistics for the instrument pairings used for analysis.

Instr. Pair (Group 1 Speed)	Slope	y-Intercept	R^2	corr.
SG33 vs DVS28	1.005	0.756	0.980	0.990
ADCP@66m vs DVS28	1.028	0.269	0.967	0.984
SG33 vs ADCP@63m	0.924	0.961	0.940	0.975
ADCP@63m vs ADCP@66m	1.002	0.152	0.951	0.977
Instr. Pair (Group 1 Direction)	Slope	y-Intercept	R^2	corr.
SG33 vs DVS28	0.931	16.189	0.953	0.976
ADCP@66m vs DVS28	0.952	9.446	0.938	0.969
SG33 vs ADCP@63m	0.965	11.089	0.931	0.966
ADCP@63m vs ADCP@66m	0.992	0.859	0.956	0.98
Instr. Pair (Group 2 Speed)	Slope	y-Intercept	R^2	corr.
SG20 vs RCM8	0.931	1.452	0.949	0.974
ADCP@74m vs RCM8	0.916	0.72	0.911	0.967
SG20 vs ADCP@72m	0.972	1.177	0.942	0.972
ADCP@72m vs ADCP@74m	0.996	0.093	0.958	0.987
Instr. Pair (Group 2 Direction)	Slope	y-Intercept	R^2	corr.
SG20 vs RCM8	1.005	4.236	0.951	0.975
ADCP@74m vs RCM8	1.058	-7.68	0.923	0.962
SG20 vs ADCP@72m	0.969	7.036	0.946	0.977
ADCP@72m vs ADCP@74m	0.986	2.441	0.973	0.991

Table 4: Instrument uncertainties as specified by the manufacturers.

Instrument	Speed (cm s^{-1})	Direction (Deg)
SG33	0.33 (std = 0.3 acc=0.15)	5 (tilt < 15 deg)
DVS28	0.31 (std = 0.3 acc=0.5% @13 cm s^{-1})	5
SG20	0.33 (std = 0.3 acc=0.15)	5 (tilt < 15 deg)
RCM8	1.0	5 if speed > 5 cm s^{-1} 7.5 if speed <= 5 cm s^{-1}
ADCP	0. 86 (std = 0.85 acc=0.5% @13 cm s^{-1})	5

Table 5: Mean and RMS measurement differences. dAB is the expected RMS difference based on manufacturer reported uncertainties. All speeds in cm s^{-1} and directions in degrees.

Group 1	Mean Δspd	RMS Δspd	dAB	Mean Δdir	RMS Δdir	dAB
SG33-DVS28	0.8	1.2	0.45	0.2	13.7	7.1
ADCP@66m-DVS28	0.6	1.3	0.9	-1.8	15.3	7.1
SG33 DCP@63	0.1	1.5	0.9	3.2	17.0	7.1
ADCP@63m-ADCP@66m	0.2	1.4	1.2	-1.0	13.2	7.1
Group 2	**Mean Δspd**	**RMS Δspd**	**dAB**	**Mean Δdir**	**RMS Δdir**	**dAB**
SG20-RCM8	0.7	1.6	1.05	5.4	15.1	7.1
ADCP@74m-RCM8	-0.2	1.6	1.3	5.4	19.6	7.1
SG20-ADCP@72m	0.9	1.6	0.9	-0.01	14.2	7.1
ADCP@72m-ADCP@74m	0.05	1.0	1.2	-0.7	9.1	7.1
Group 3	**Mean Δspd**	**RMS Δspd**	**dAB**	**Mean Δdir**	**RMS Δdir**	**dAB**
SG33-RCM8	0.4	3.0	1.05	6.4	25.6	7.1
ADCP@74m-RCM8	-0.2	1.6	0.9	5.4	19.6	7.1
SG33-ADCP@63m	0.1	1.5	0.9	3.2	17.0	7.1
ADCP@63m-ADCP@74m	0.6	3.6	1.2	-1.4	30.2	7.1

Table 6: Estimate of vertical shear across the instrument range

	RMS_{Tot}	RMS_{Inst}	Shear (11 m)	Shear (1 m)
Mean Speed (cm s^{-1})	3.3	1.5	2.9	0.27
Mean Direction (Deg)	27.5	18	20.8	1.9
Upper Speed (cm s^{-1})	3.6	1	3.45	0.31
Upper Direction (Deg)	30	10	28.3	2.6
Lower Speed (cm s^{-1})	3	1.6	2.54	0.23
Lower Direction (Deg)	25	20	15	1.4

FIGURES

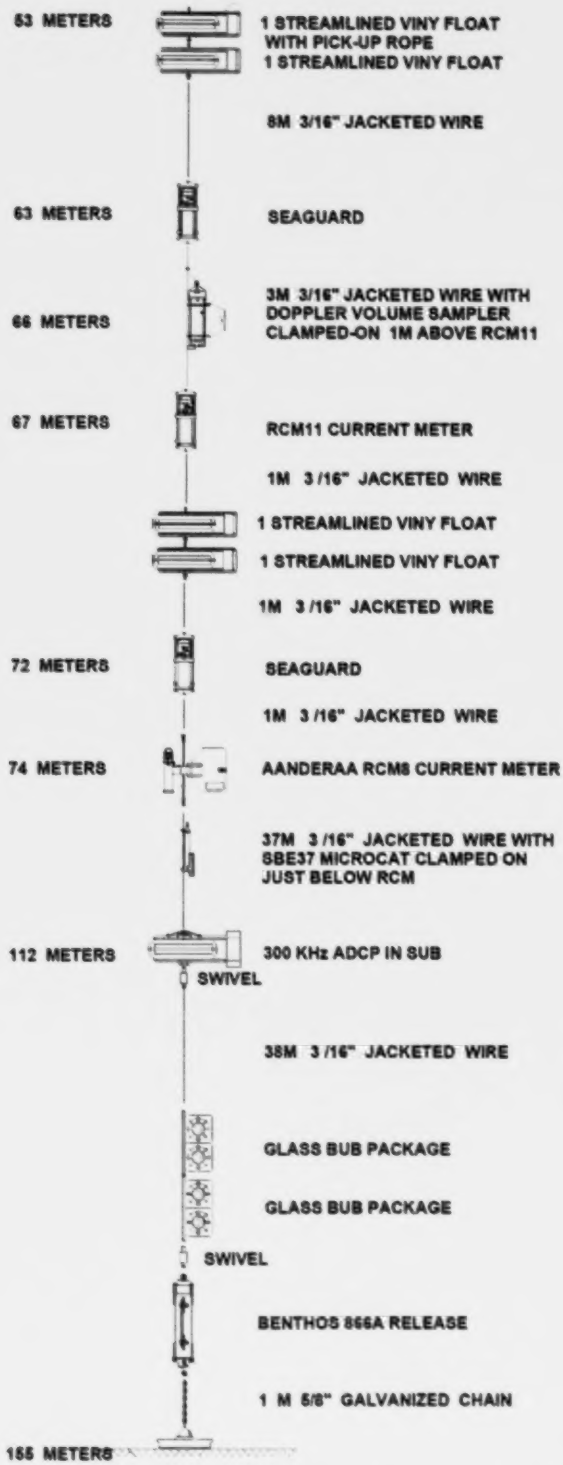

Figure 1: Schematic of the current meter comparison mooring (1681) deployed at HL2 in May 2008.

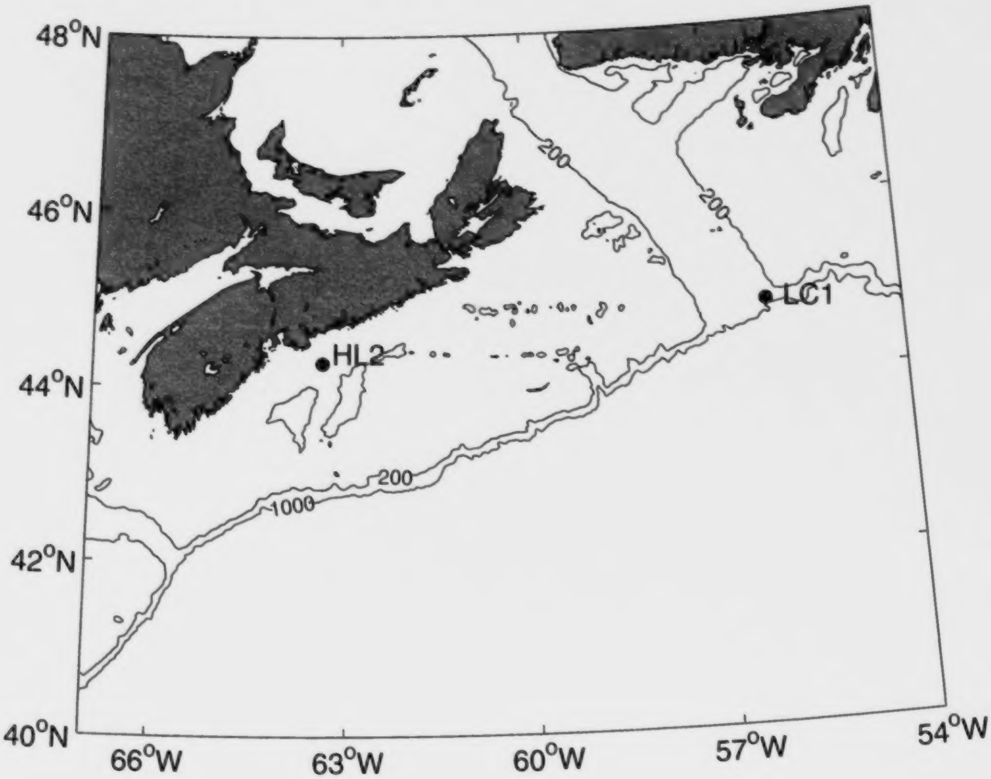

Figure 2: Map of Scotian Shelf showing the locations of the 2008 comparison mooring HL2 (latitude: 44° 17.53' N, longitude 63° 16.04'W) and the 2003 mooring in Laurentian Channel LC1 (latitude: 44° 49.88' N, longitude 56° 48.00'W).

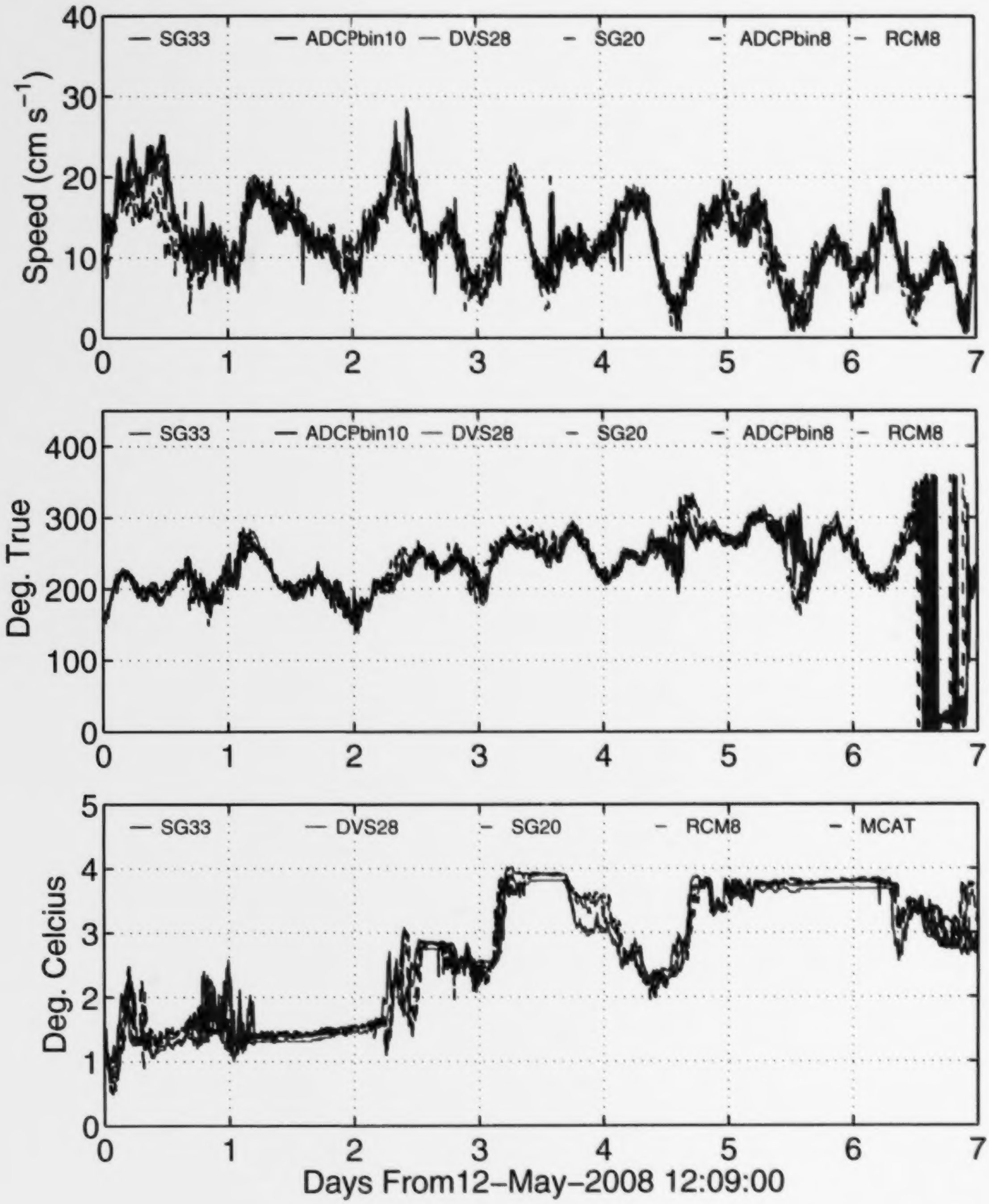

Figure 3: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat (Part 1).

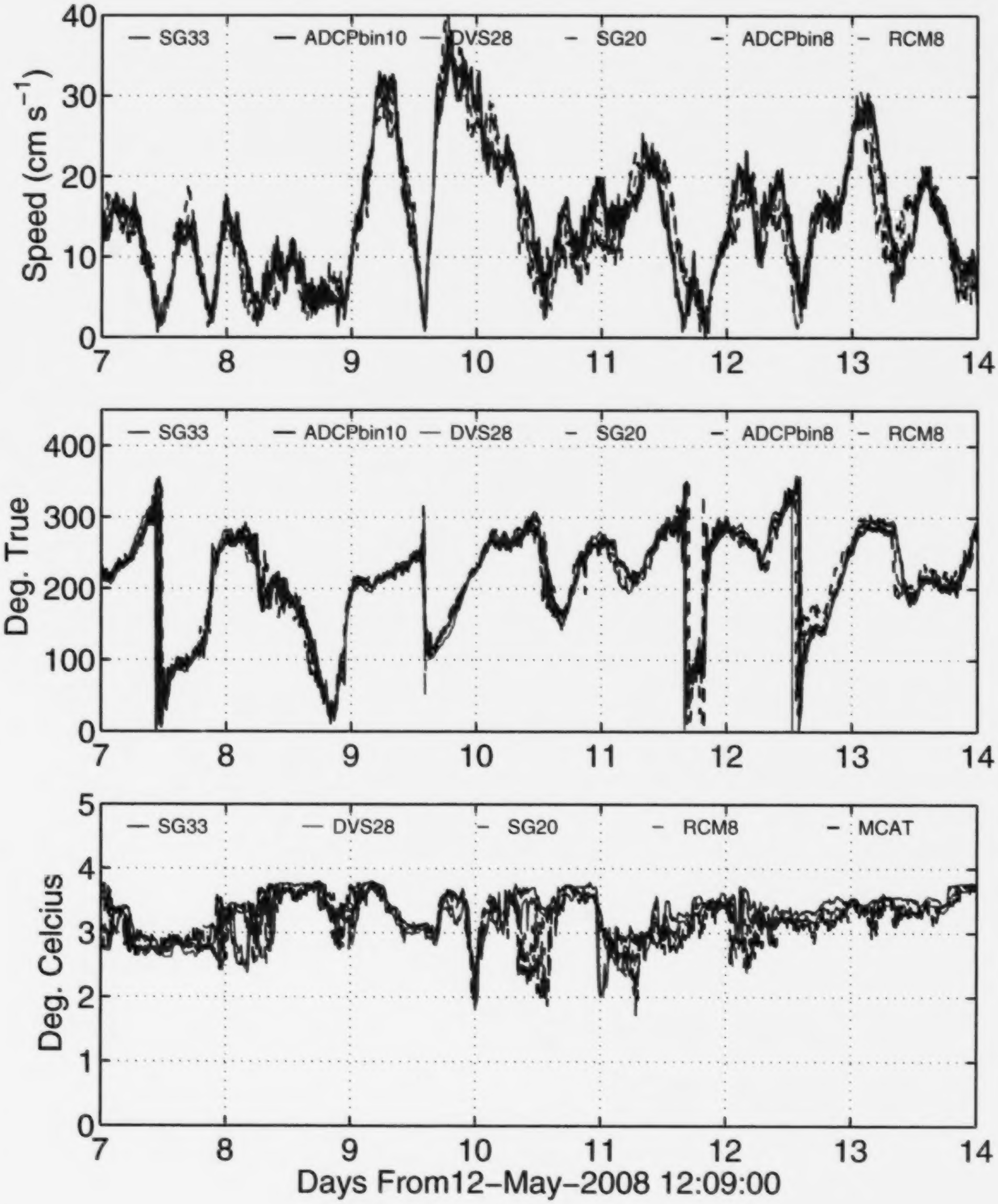

Figure 4: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat (Part 2).

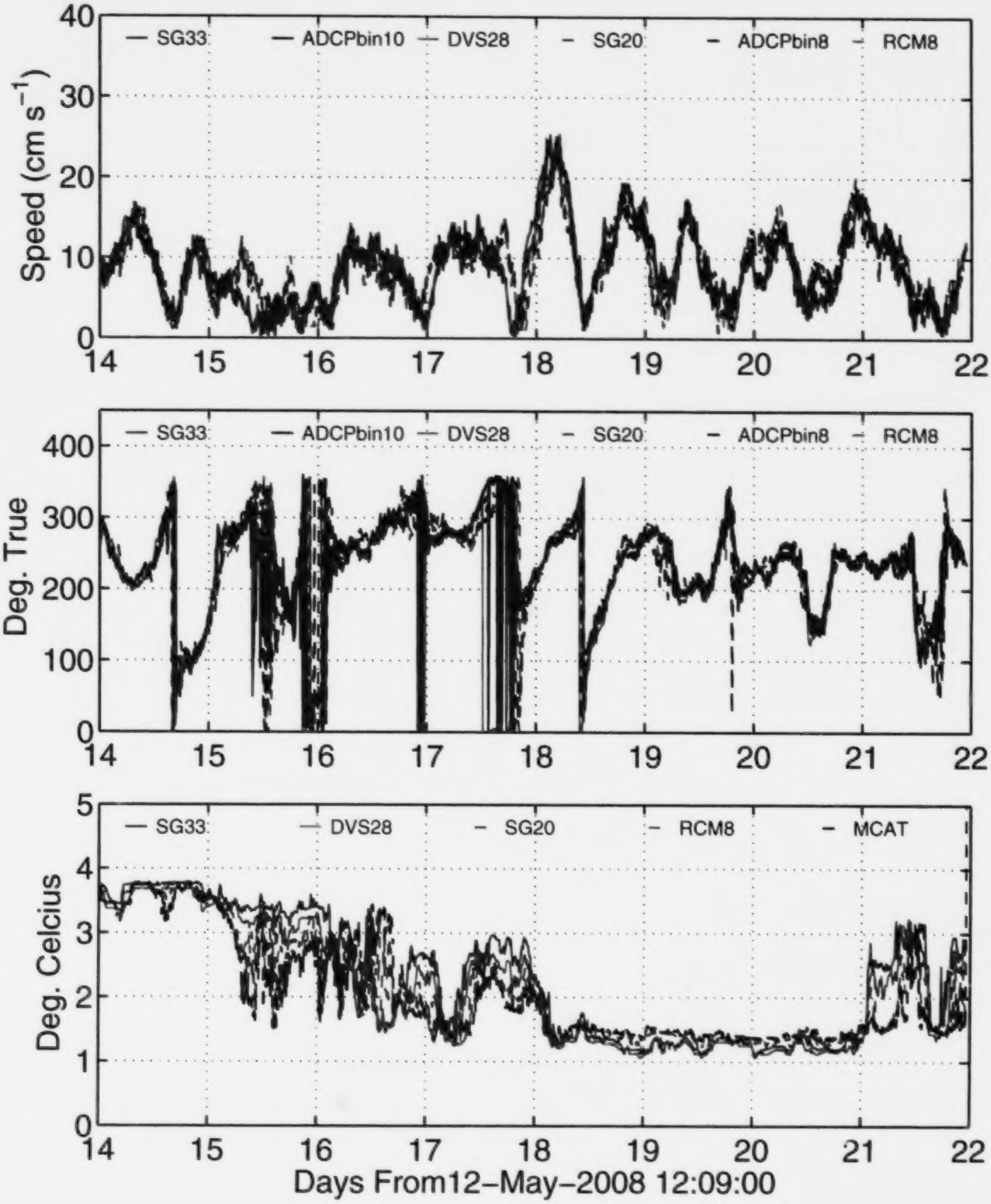

Figure 5: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat (Part 3).

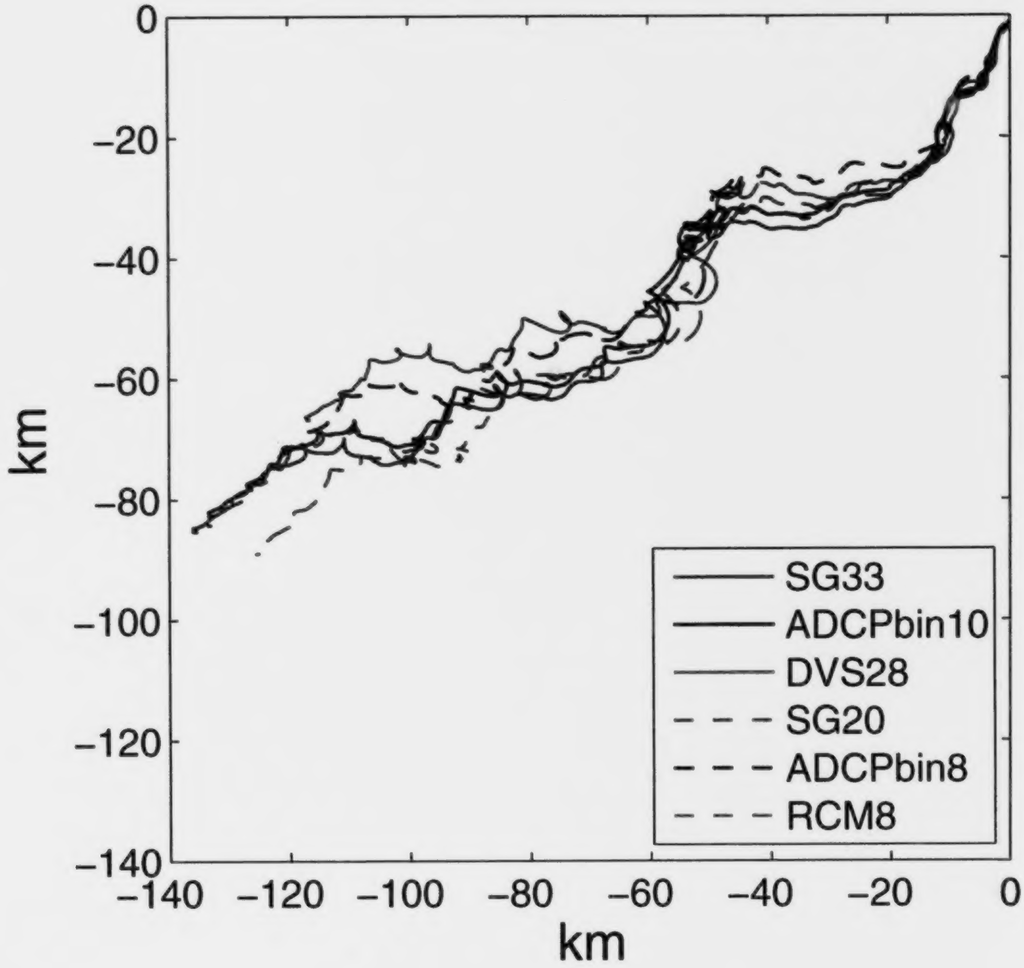

Figure 6: Progressive vector diagram of the data collect with the current meters at HL2.

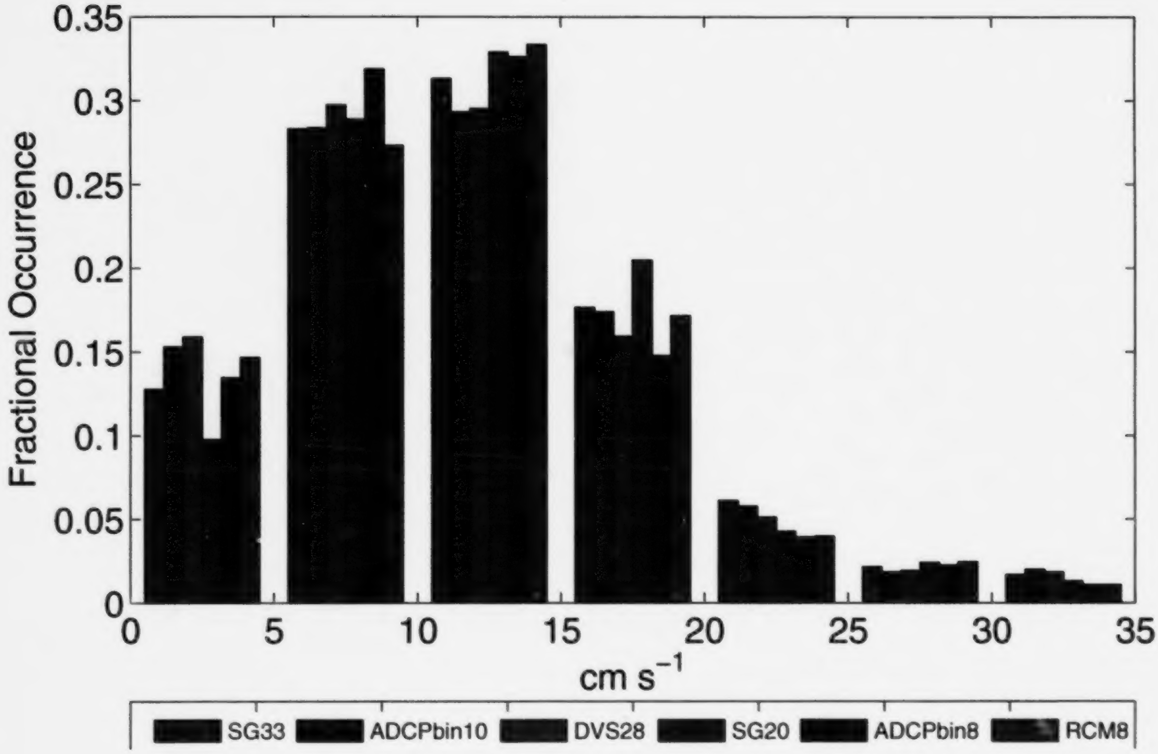

Figure 7: Speed distribution of data binned in 5 cm s^{-1} intervals.

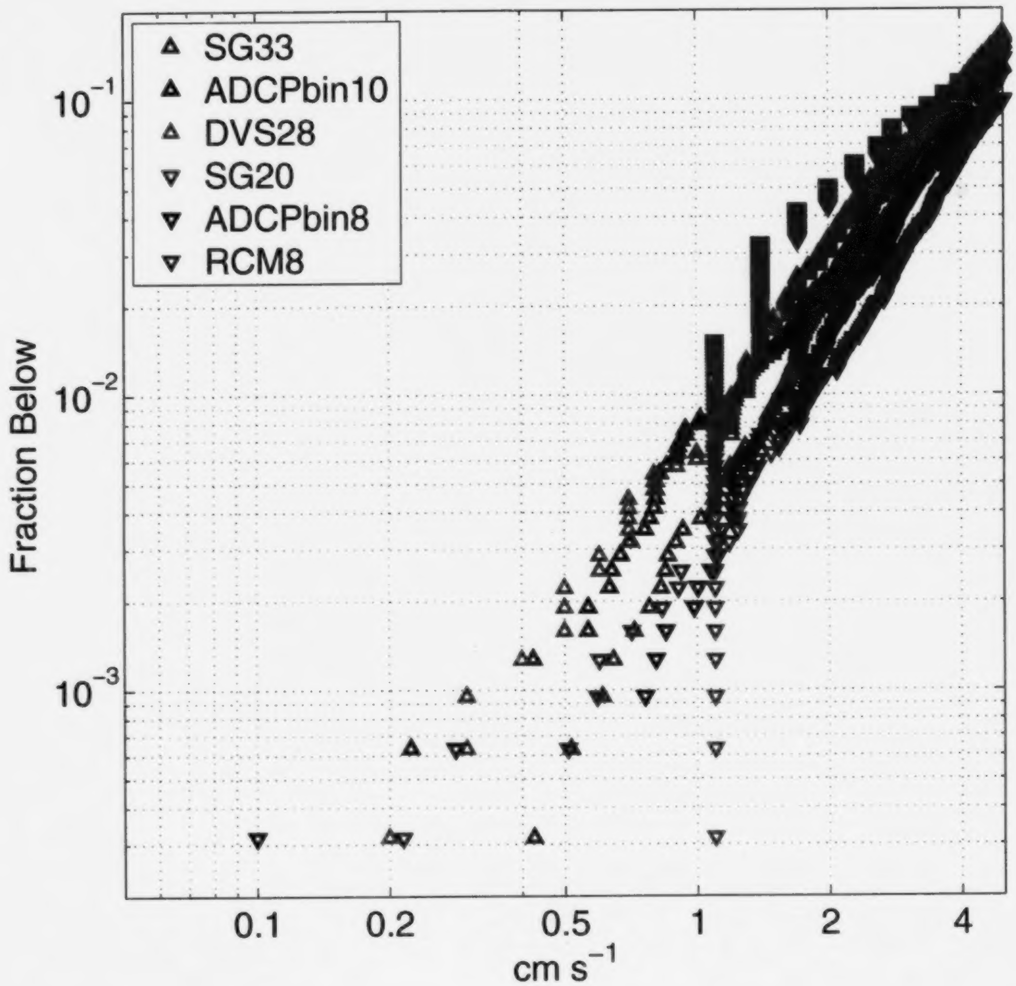

Figure 8: Cumulative speed distribution showing the fraction of observations below particular speeds. The steep drop in the RCM8 at 1.2 cm s^{-1} is due to the calibration cutoff 1,1 cm s^{-1} for this instrument.

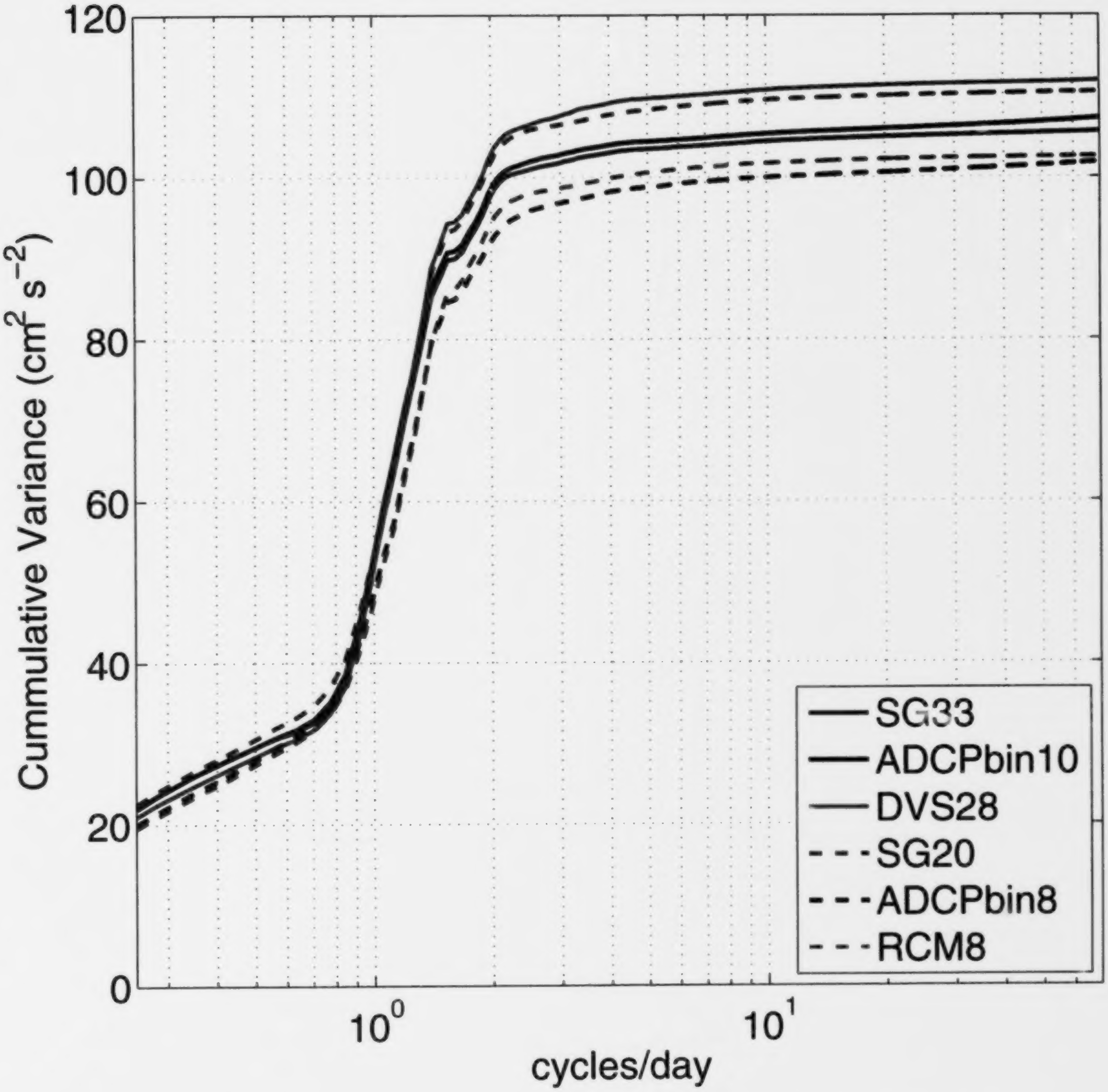

Figure 9: Cumulative power spectrum expressed as variance. Accumulation is from zero frequency.

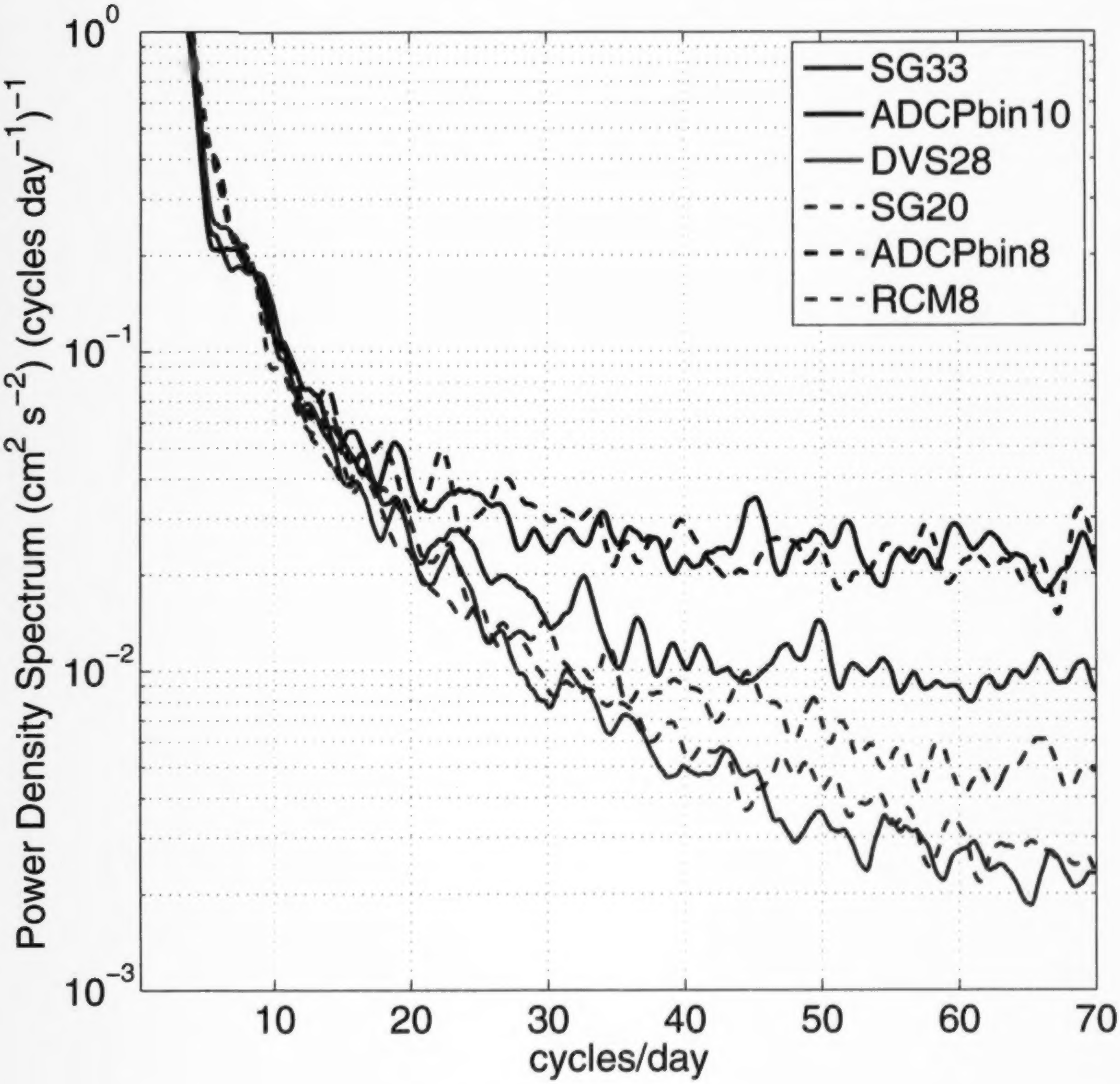

Figure 10: Spectral Power Distribution from current meter time series expressed as variance per unit frequency

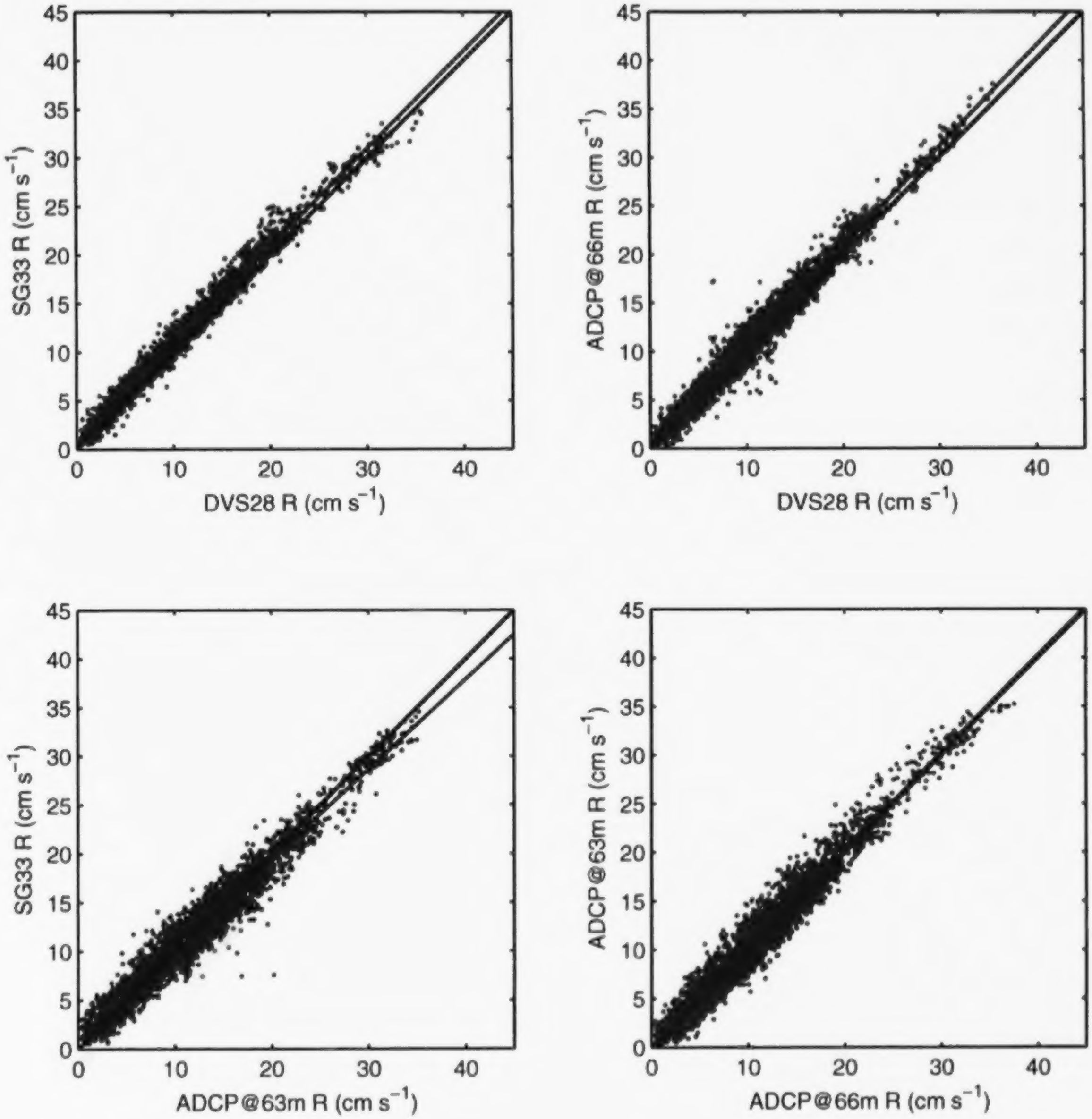

Figure 11 Scatter plot of speed for instruments in Group 1

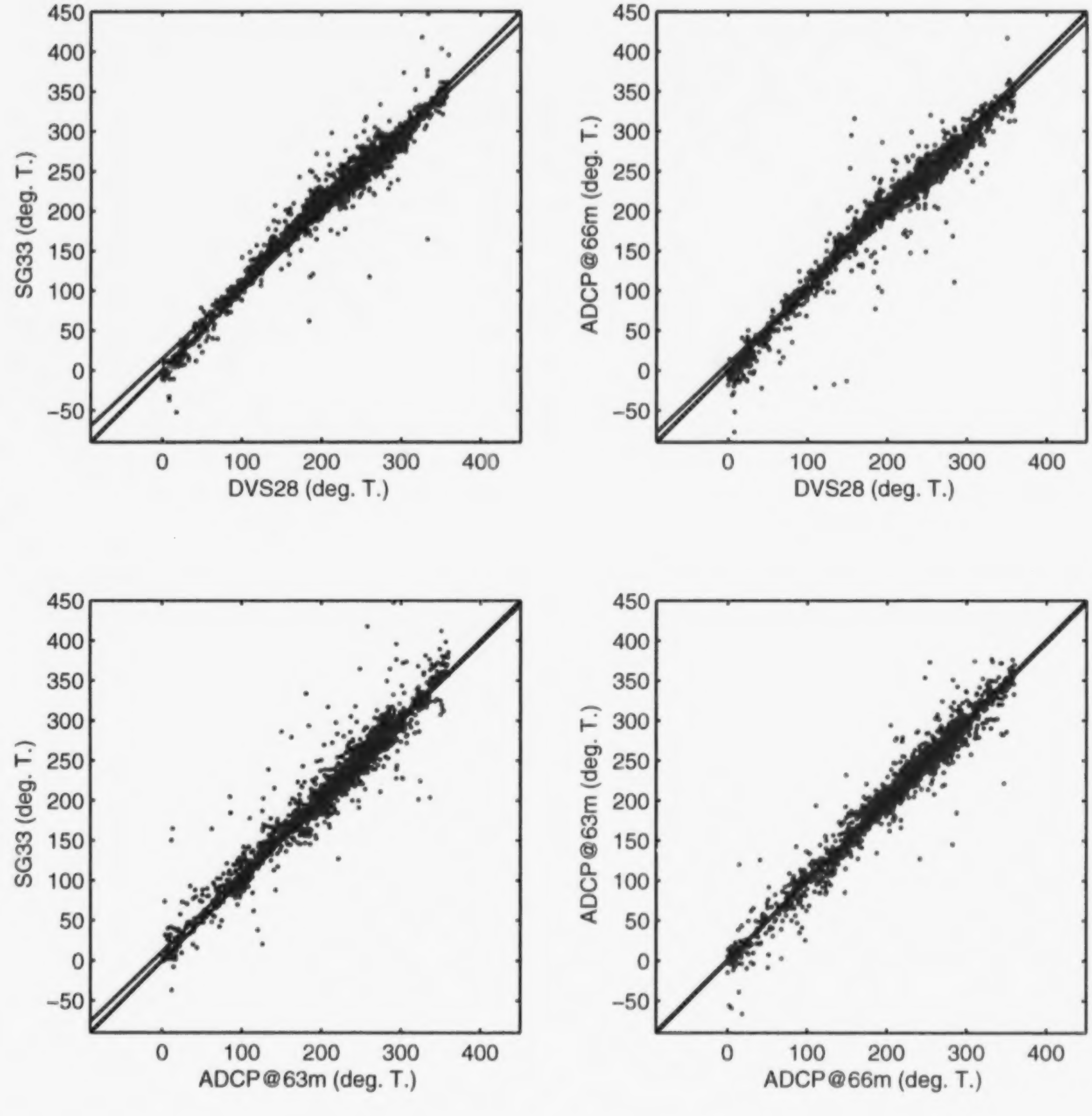

Figure 12 Scatter plot of direction for instruments in Group 1

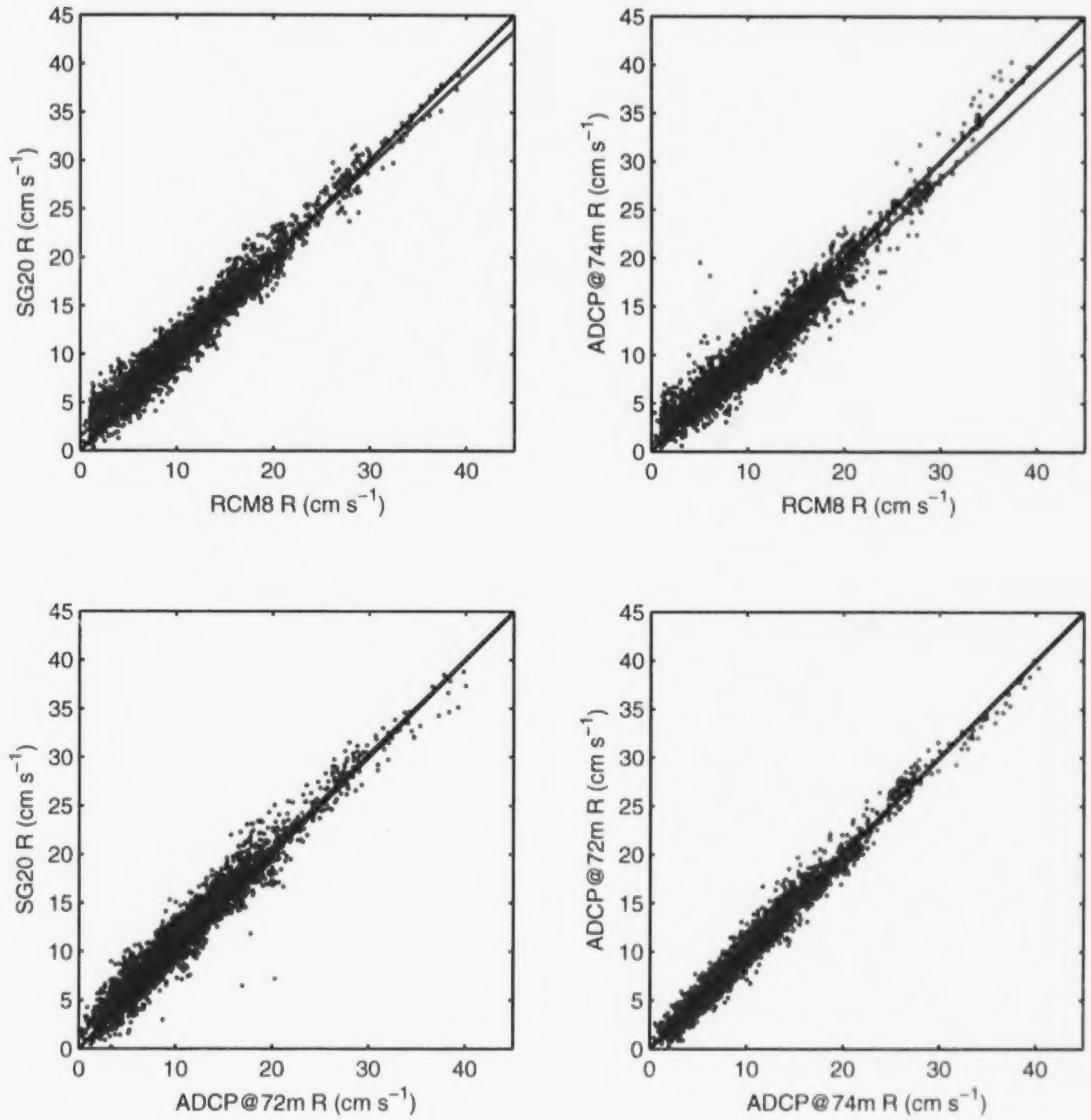

Figure 13 Scatter plot of speed for instruments in Group 2.

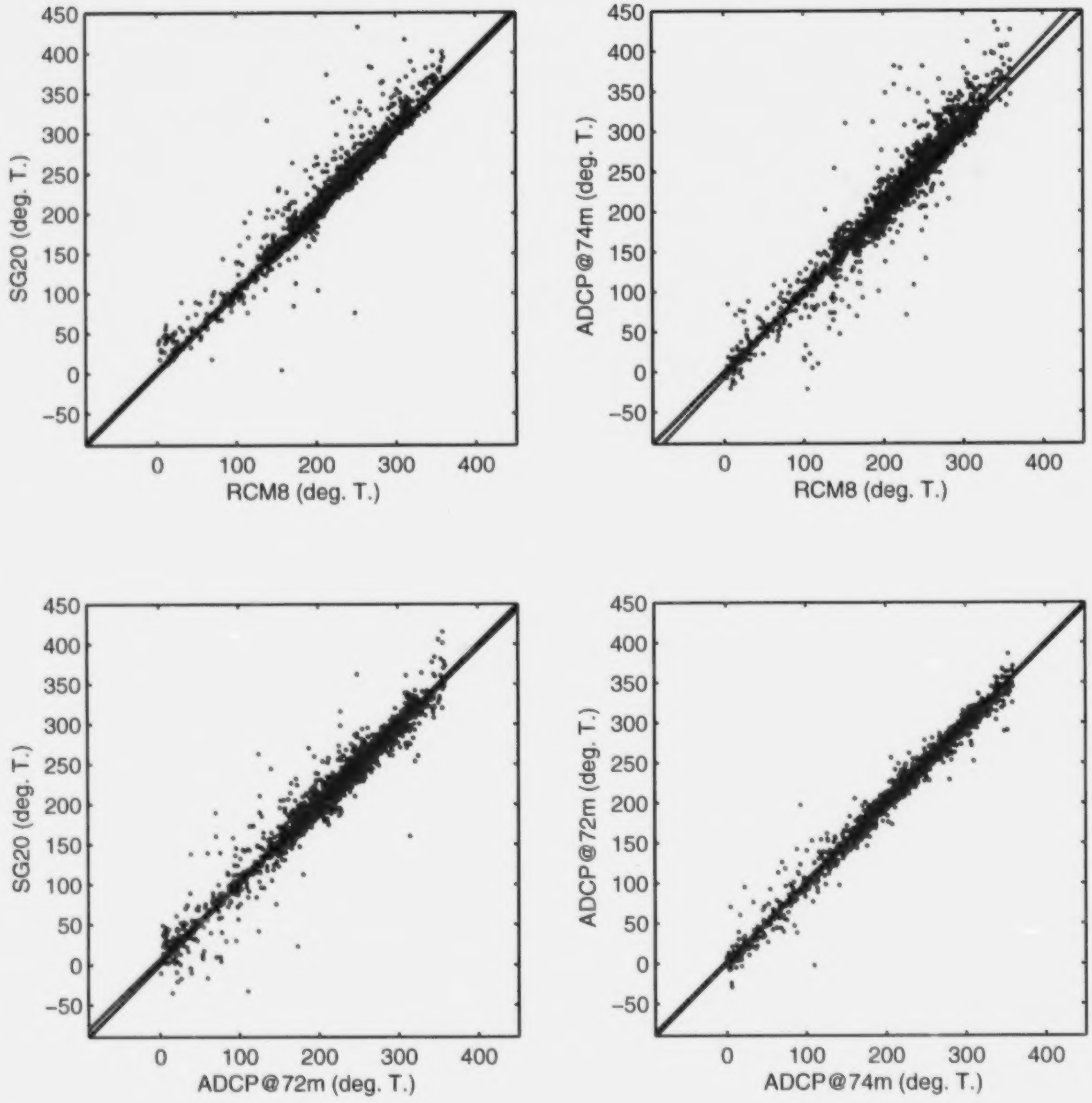

Figure 14: Scatter plot of direction for instruments in Group 2.

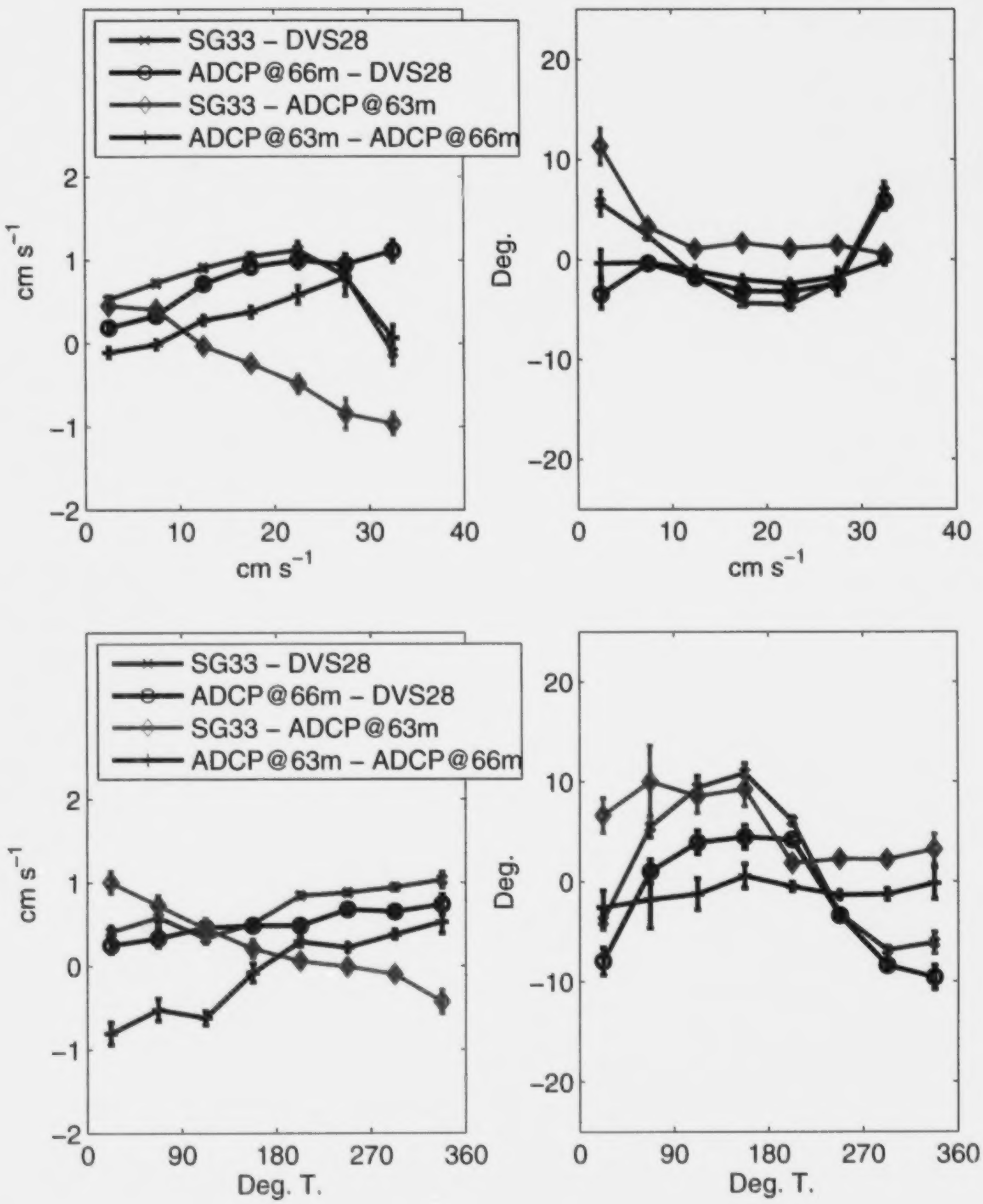

Figure 15: Mean difference in speed (left panels) and direction (right panels) between instruments in Group 1 as a function of speed (upper panels) and direction (lower panels).

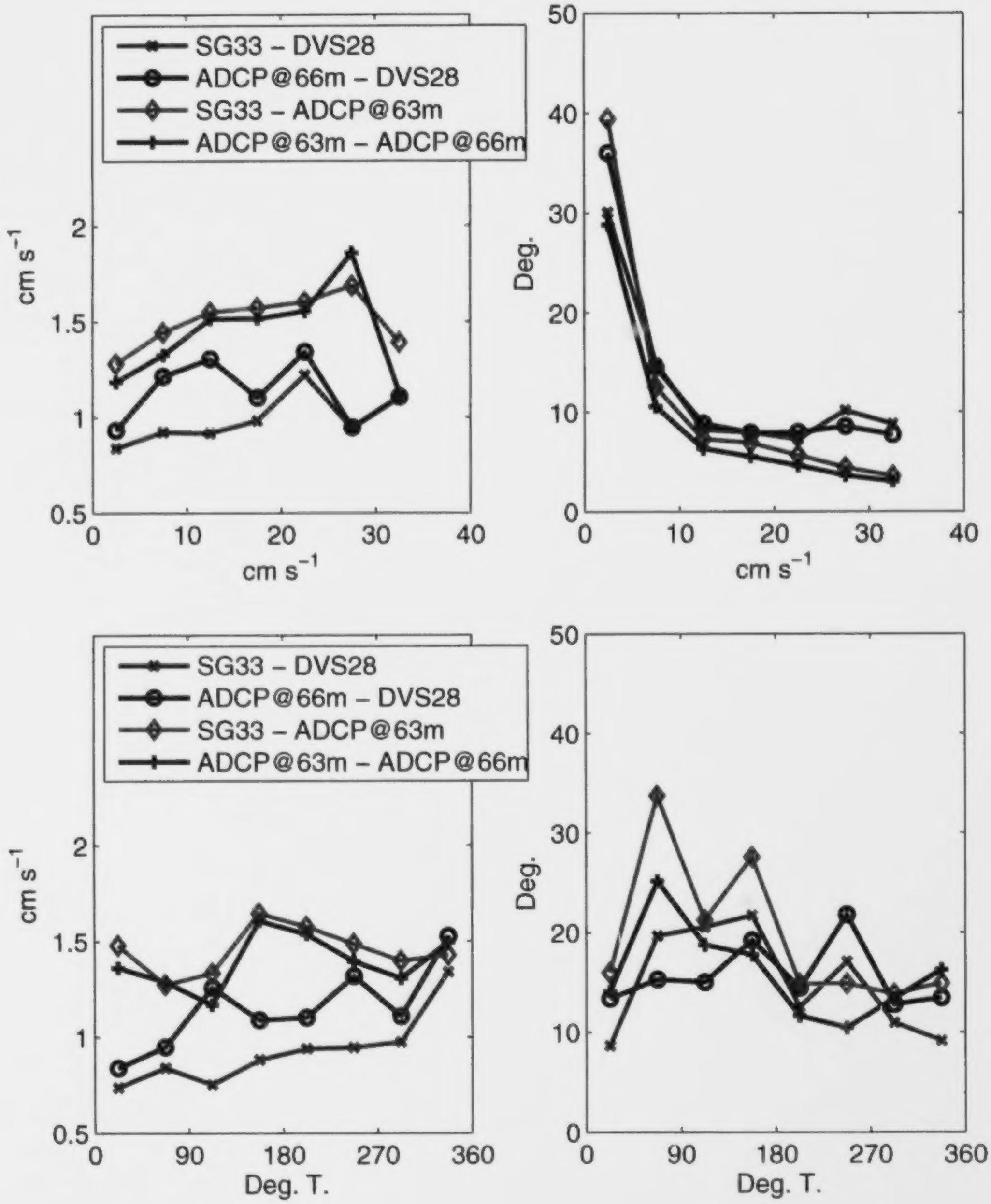

Figure 16: RMS difference in speed (left) and direction (right) between instruments in Group 1. Shown is the distribution with speed (upper) and direction (lower).

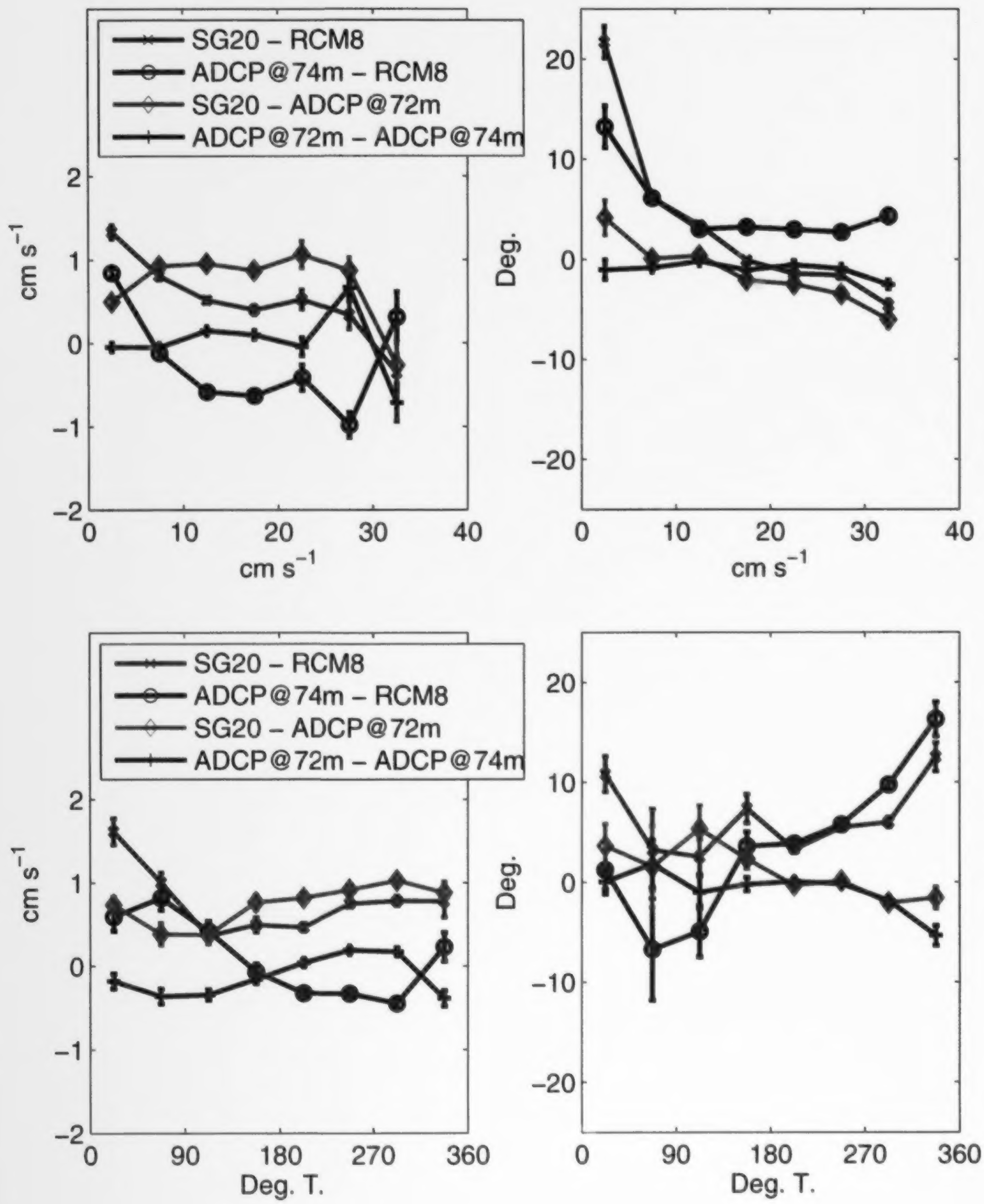

Figure 17: Mean difference between instruments in Group 2 as a function of speed and direction.

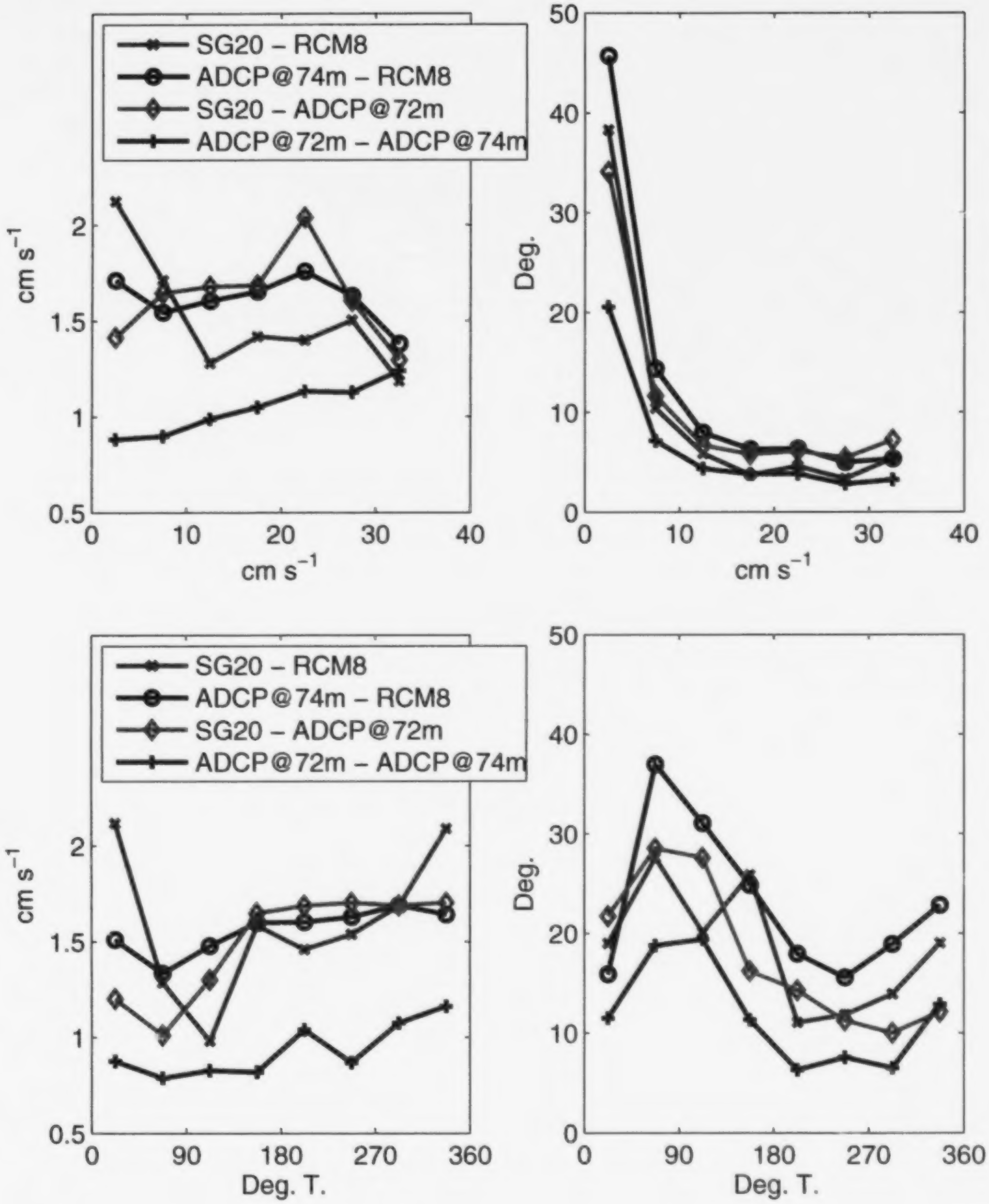

Figure 18: RMS difference between instruments in Group 2. Shown is the distribution with speed and direction.

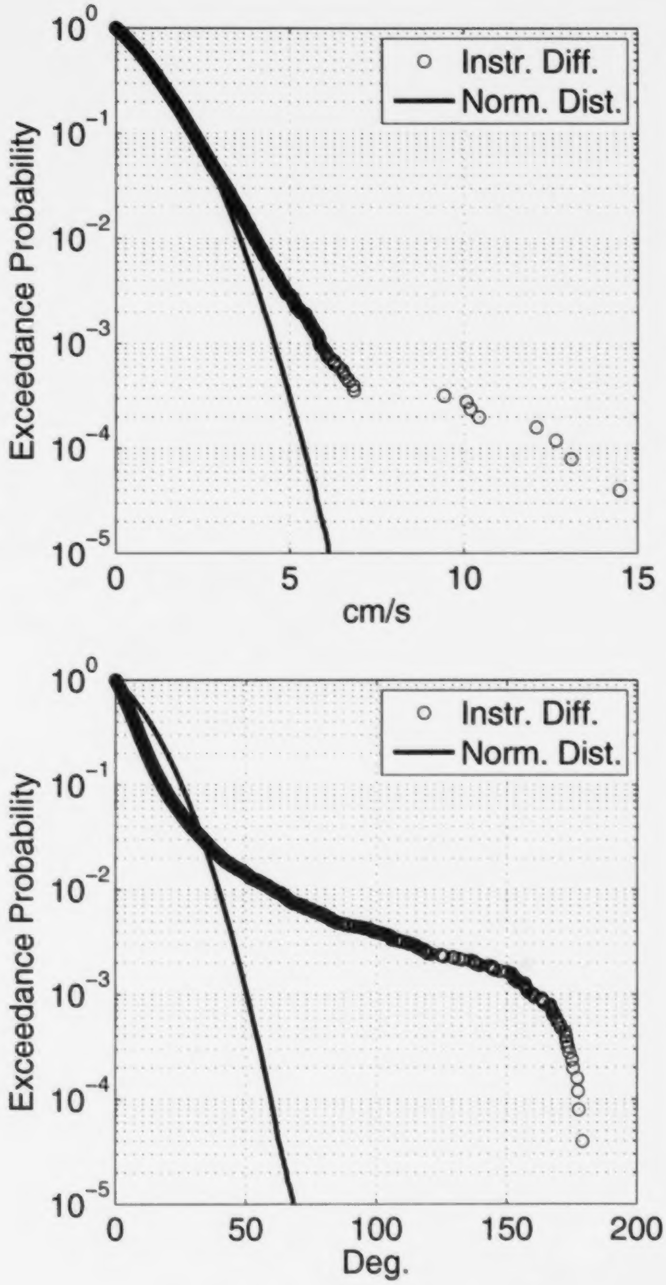

Figure 19 Exceedance probabilities of instrument speed (top) and direction (bottom) differences for all pairs in Groups 1 and 2, based on a ranking of the absolute values of the differences. Also shown is a normal distribution derived from the mean and standard deviation of all the differences.

APPENDIX A: RCM8 vs RCM11 COMPARISONS FROM PREVIOUS DEPLOYMENTS

In 2003 and 2007, deployments moorings were undertaken on which RCM8s and RCM11s were placed adjacent to each other for the purposes of intercomparison. The 2003 deployment (BIO mooring #1492) was at site LC1 in the Laurentian Channel (see Figure 2) for the period of 17-Jul-03 to 05-Nov-03. The 2007 deployment (BIO mooring #1657) was at site HL2 on the Scotian Shelf for the period of 02-Aug-07 to 28-Sep-07.

MOORING # 1657 ADCP GREENAN HFX LINE STN# 2 AUG 2007

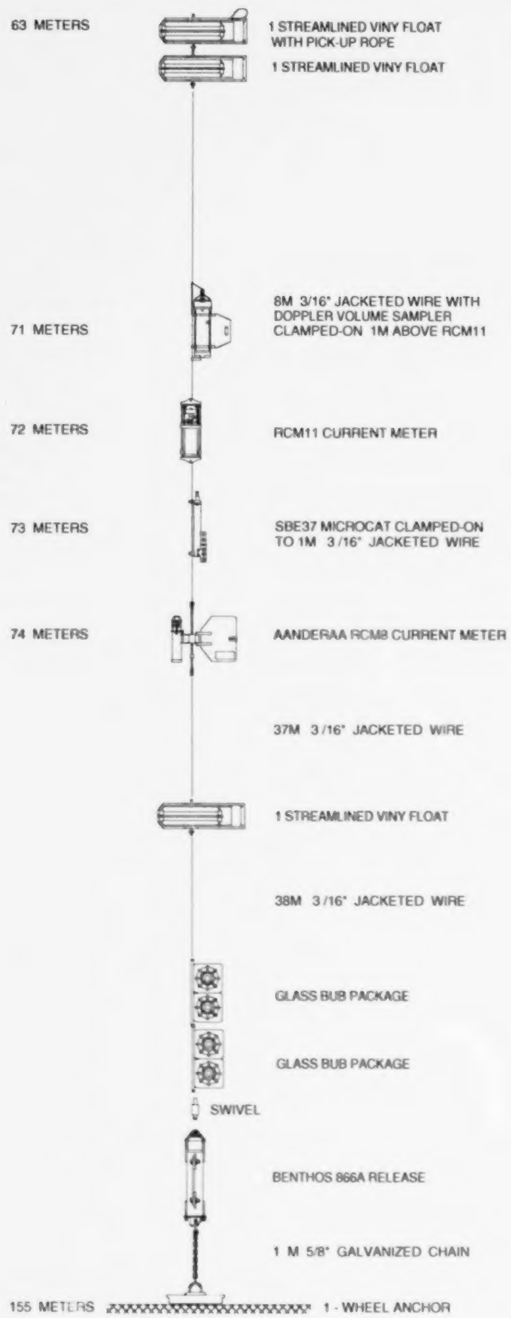

Figure A1: Mooring diagram for HL2 mooring site in 2007.

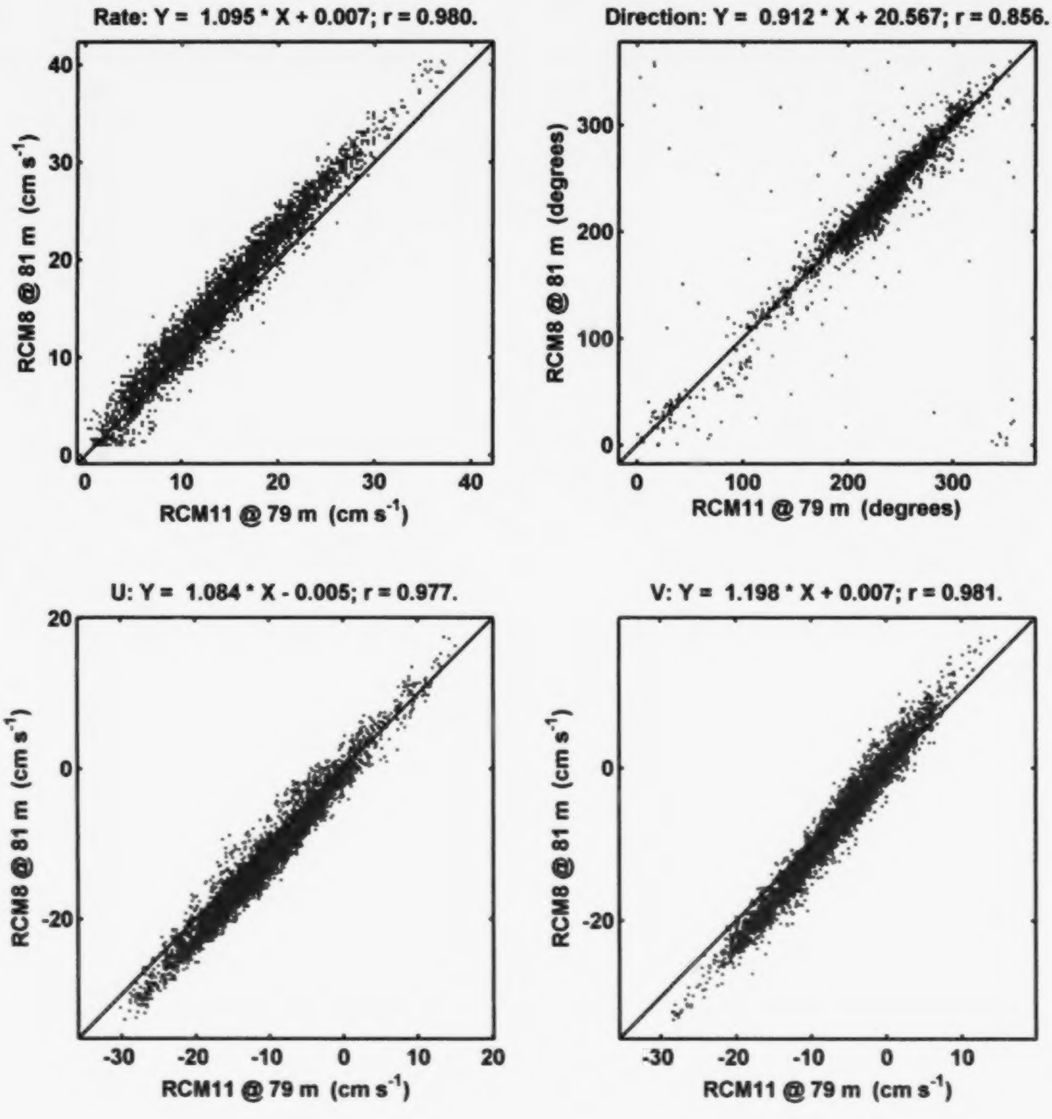

Figure A2: Comparison of RCM8 and RCM11 rate, direction, u-component and v-component of velocity from mooring deployed at HL2 in 2007.

MOORING # 1492 JOHN LODER LAURENTIAN CHANNEL JULY 2003

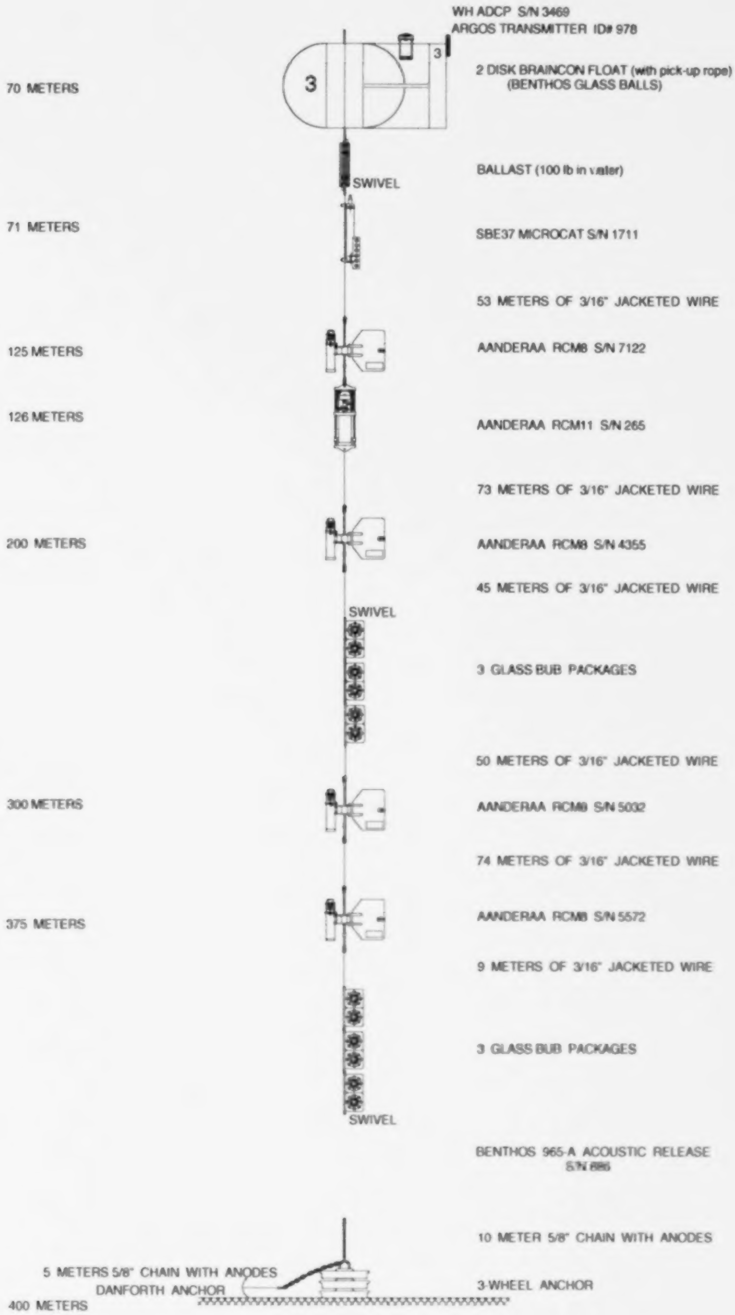

Figure A3: Mooring diagram for LC1 mooring site in 2003.

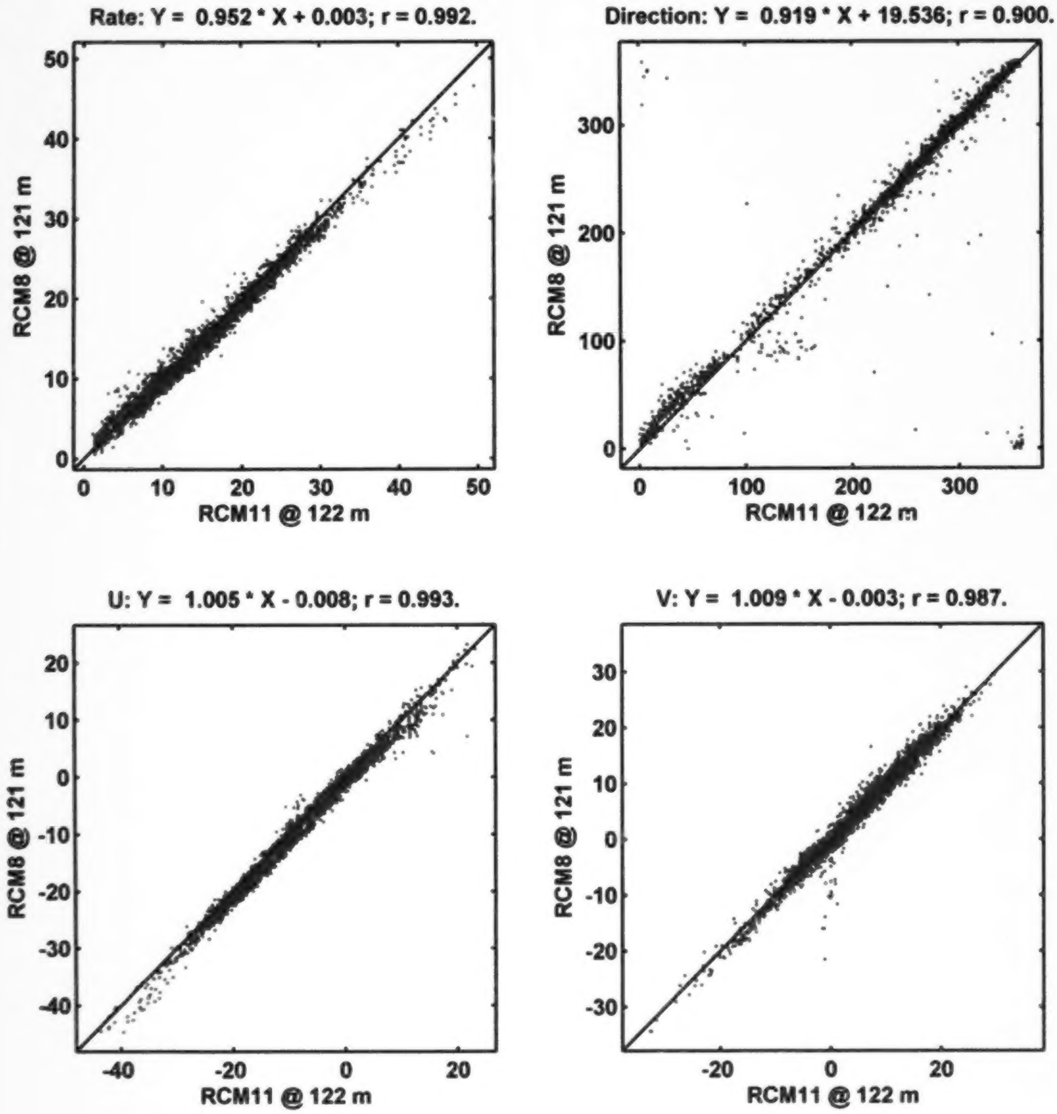

Figure A4: Comparison of RCM8 and RCM11 rate, direction, u-component and v-component of velocity from mooring deployed at LC1 in 2003.

APPENDIX B: EXAMPLES OF LARGE INSTRUMENT DISAGREEMENT

This appendix includes the few occasions during which large differences in speed and direction were observed between instruments during the deployment. Note the large discrepancies in speed and direction from the current meters tend to occur when the temperature structure of the water column is highly variable. This is likely associated with internal wave activity at this mooring site.

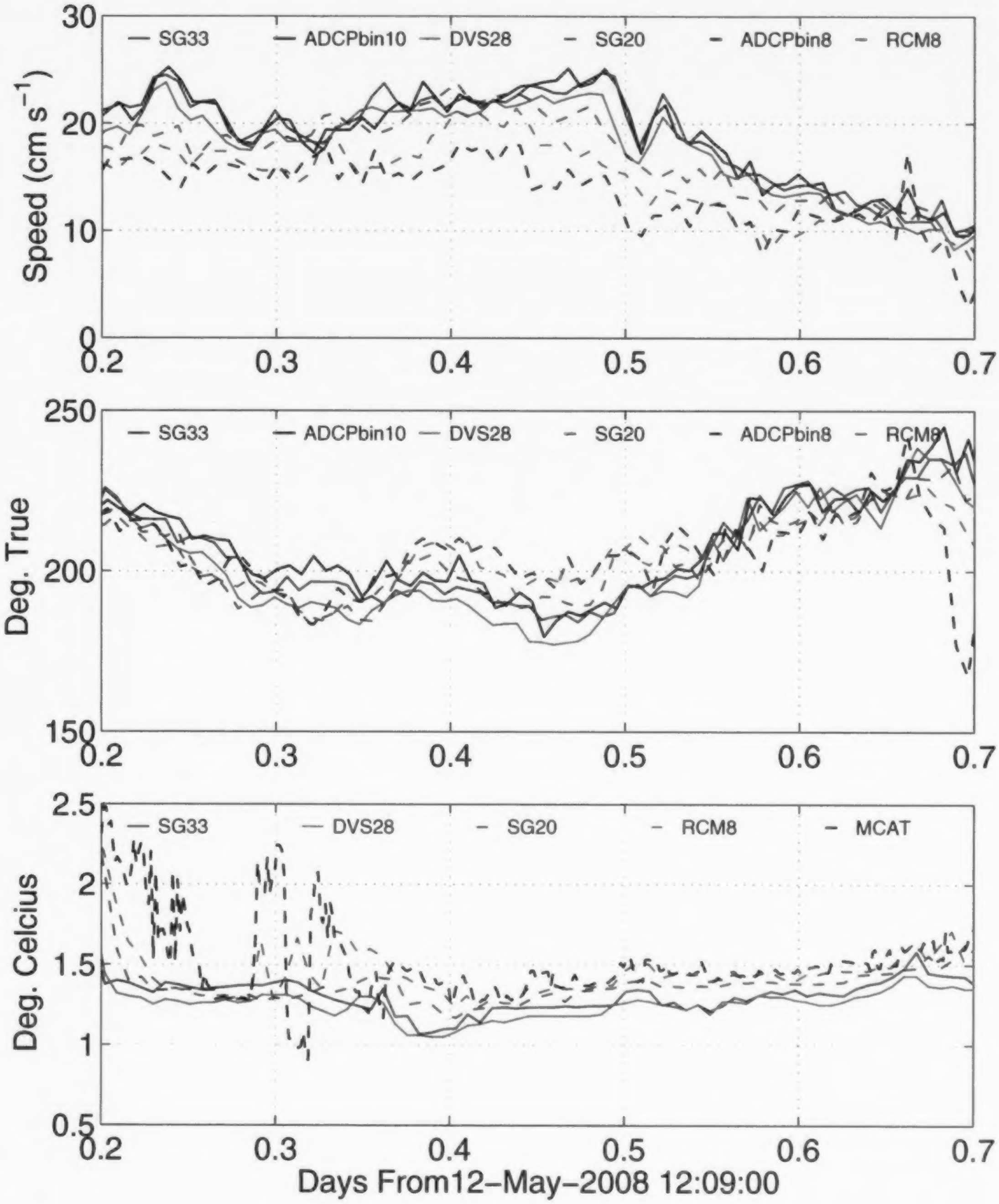

Figure B1: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat.

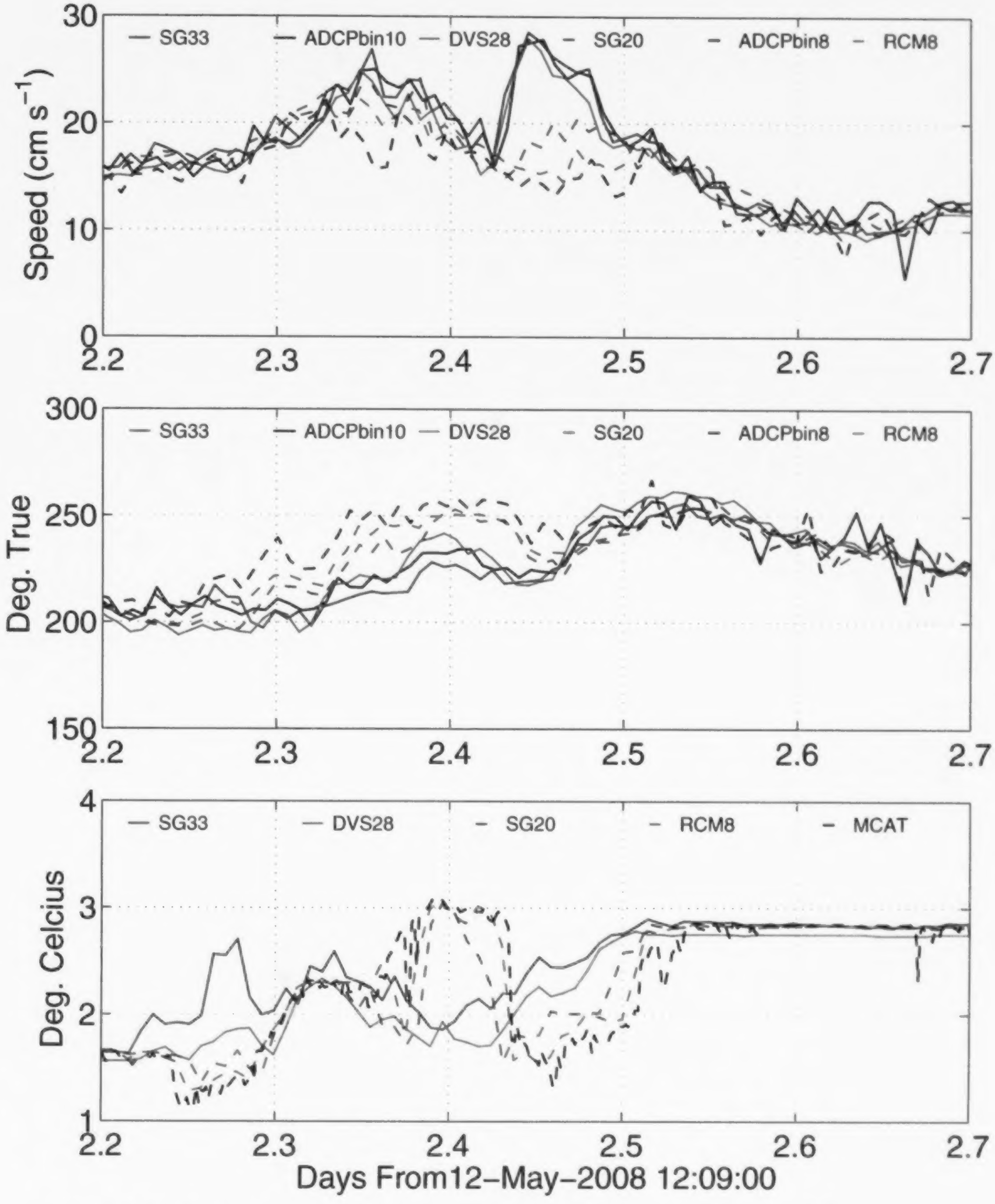

Figure B2: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat.

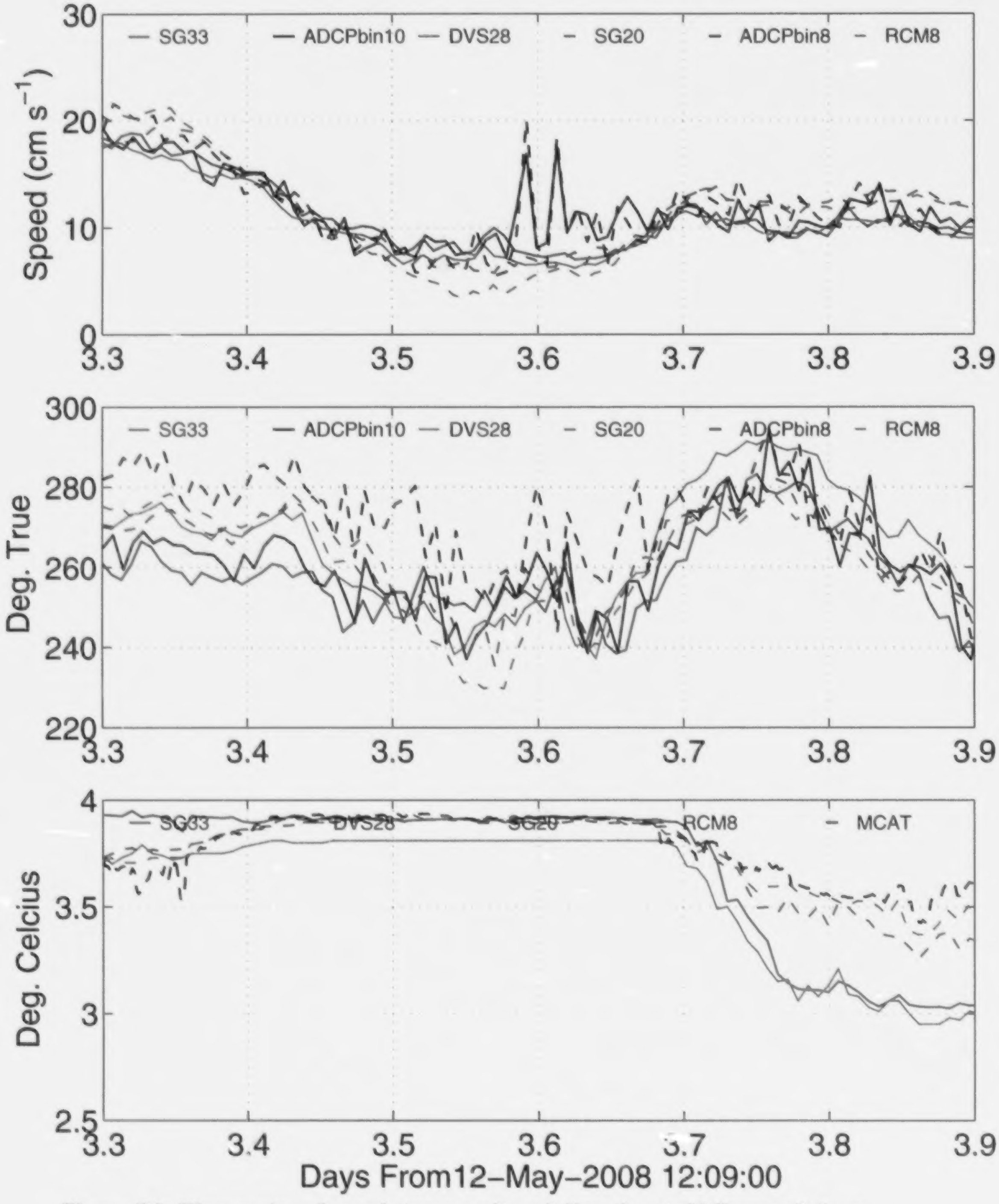

Figure B3: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat.

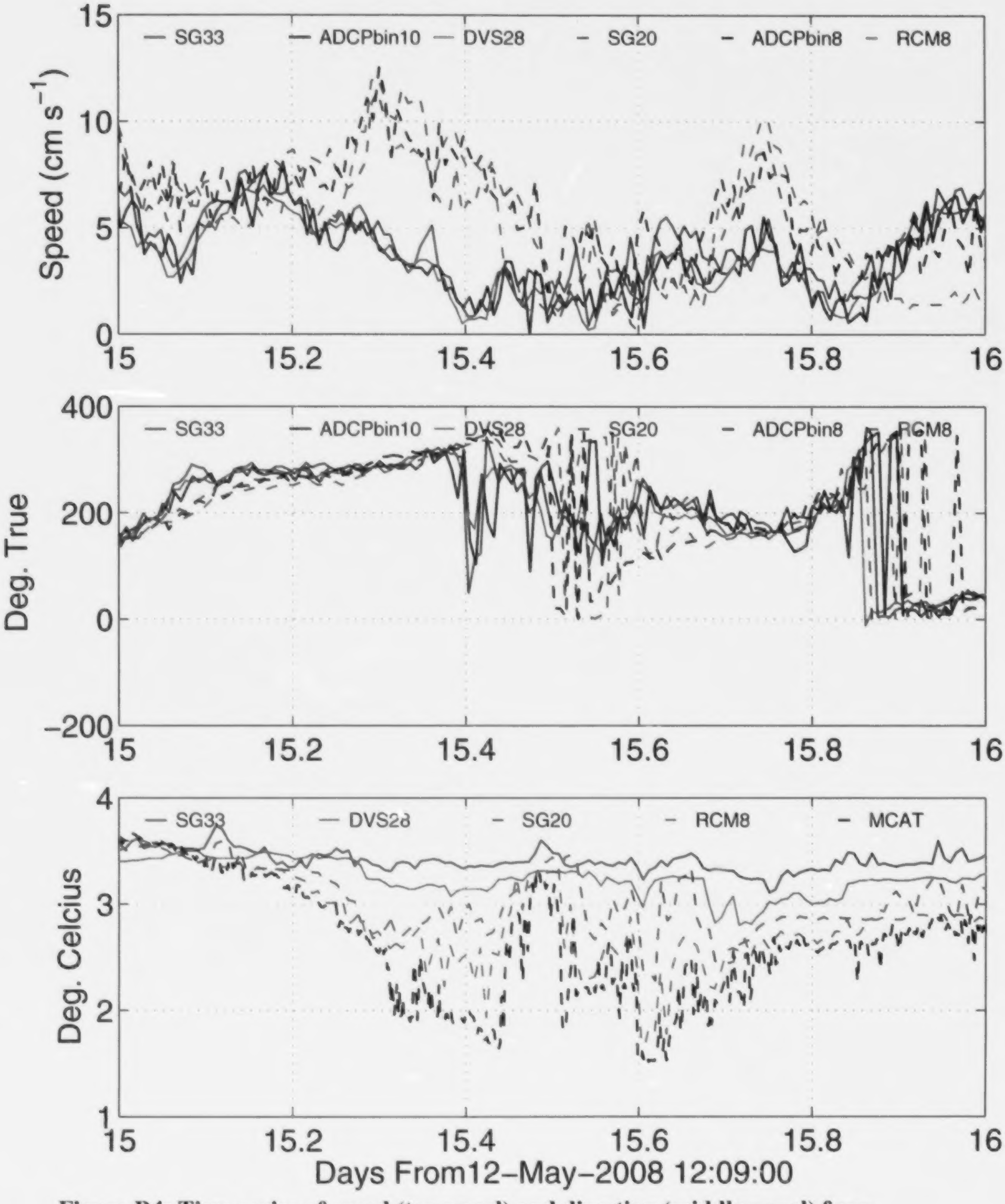

Figure B4: Time series of speed (top panel) and direction (middle panel) from various current meters and temperature (bottom panel) from current meters and Microcat.

APPENDIX C: DAILY PROGRESSIVE VECTORS DIAGRAMS

This appendix includes daily PVD diagrams and tables to summarize the displacement of water parcels during the mooring period.

Day	Distance (km)			Displacement (km)		
	SG33	ADCP	DVS	SG33	ADCP	DVS
1	14.2	13.9	13	13.7	13.3	12.4
2	11.3	11.1	10.7	10.3	10	9
3	12.6	12.4	11.8	11.7	11.5	10.6
4	9.4	9.6	9	9	9.1	8.4
5	10.8	10.4	10	10.1	9.8	9.1
6	8.9	8.6	8.2	8.5	8.2	7.7
7	7.9	7.7	7.5	3.8	3.8	3.2
8	8.9	9	8.6	3.5	3.4	2.6
9	6.8	6.5	6.2	3.3	3.1	2.5
10	19.7	20.2	19.5	16.2	16.5	14.9
11	14.5	14.5	14	12.5	12.3	11.1
12	10.9	10.9	10.2	8.6	8.7	7.9
13	13.4	13.3	12.6	7.4	7.4	6.3
14	14.5	14.1	13.5	11.7	11.1	10
15	8.2	7.6	7.3	4.5	4	3.4
16	3.5	3.1	3	1.6	1.4	1.2
17	7.1	6.6	6.3	5.8	5.7	5.3
18	8.1	7.8	7.3	5.4	5.5	4.7
19	12.9	12.6	11.3	10	9.9	8.2
20	7.9	7.6	6.9	6.5	6.3	5.3
21	7.9	7.9	7.2	7.2	7.2	6.1
22	6.4	6.2	5.7	5.1	5	4.5
Average	**10.3**	**10.1**	**9.5**	**8.0**	**7.9**	**7.0**

Table C1: One-day progressive vector diagrams for the period of 12 May to 3 June 2008. Plots include the three current meters in Group 1 at the top of the mooring. The "Distance" is the path integral (or the gross distance traveled) the "Displacement" is the distance from starting point (net distance traveled).

Day	Distance			Displacement		
	SG20	ADCP	RCM8	SG20	ADCP	RCM8
1	13	10.8	11.5	12.5	10.4	11.1
2	12.6	12	12.6	11.1	10.3	10.9
3	12.4	11	11.6	11.3	9.9	10.5
4	10.3	10.3	10	9.7	9.7	9.4
5	10.7	10	10.2	9.7	8.9	9.4
6	9.6	9.3	9.3	8.6	8.1	8.3
7	7.8	6.6	6.4	2.7	2	2.3
8	9.5	9.2	9	3.3	3.3	3.6
9	6.7	5.7	5.5	2.8	1.7	2.3
10	19.8	19.7	19.6	16.1	16.1	16.2
11	13.8	12.5	12.9	11.6	9.9	10.6
12	11.2	11.3	11.2	8.9	8.6	8.7
13	13.1	11.8	12.2	8	8.4	8.2
14	14.2	13.1	13.9	11.4	10.3	11
15	8.4	8.1	8.2	4.7	4.2	4.7
16	4.8	5.2	4.4	2	1.8	2.1
17	6.7	6	6	5.9	5.1	5.3
18	8.3	8.5	7.9	6.5	6.7	6.5
19	12.2	10.6	11.7	9.4	8.7	9.2
20	7.8	6.6	7	6.2	5.6	6.1
21	9.7	8.9	9.6	8	7.5	8.1
22	6.9	5.9	6.2	5.8	4.9	5.4
Average	**10.4**	**9.7**	**9.8**	**8.0**	**7.4**	**7.7**

Table C2: One-day progressive vector diagrams for the period of 12 May to 3 June 2008. Plots include the three current meters in Group 2 at the bottom of the mooring. The "Distance" is the path integral (or the gross distance traveled) the "Displacement" is the distance from starting point (net distance traveled).

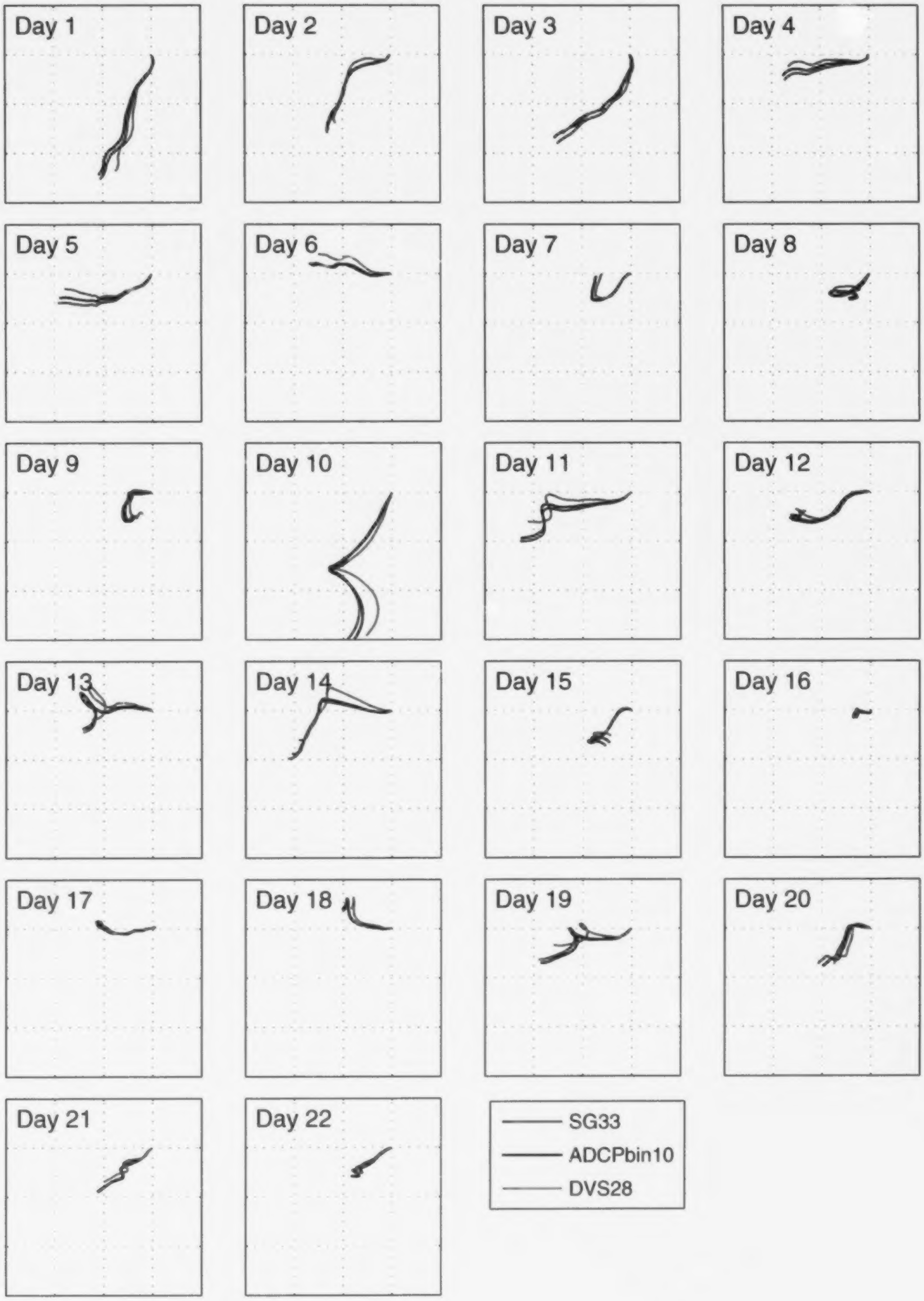

Figure C1: One-day progressive vector diagrams for the period of 12 May to 3 June 2008. Plots include the three current meters in Group 1 at the top of the mooring.

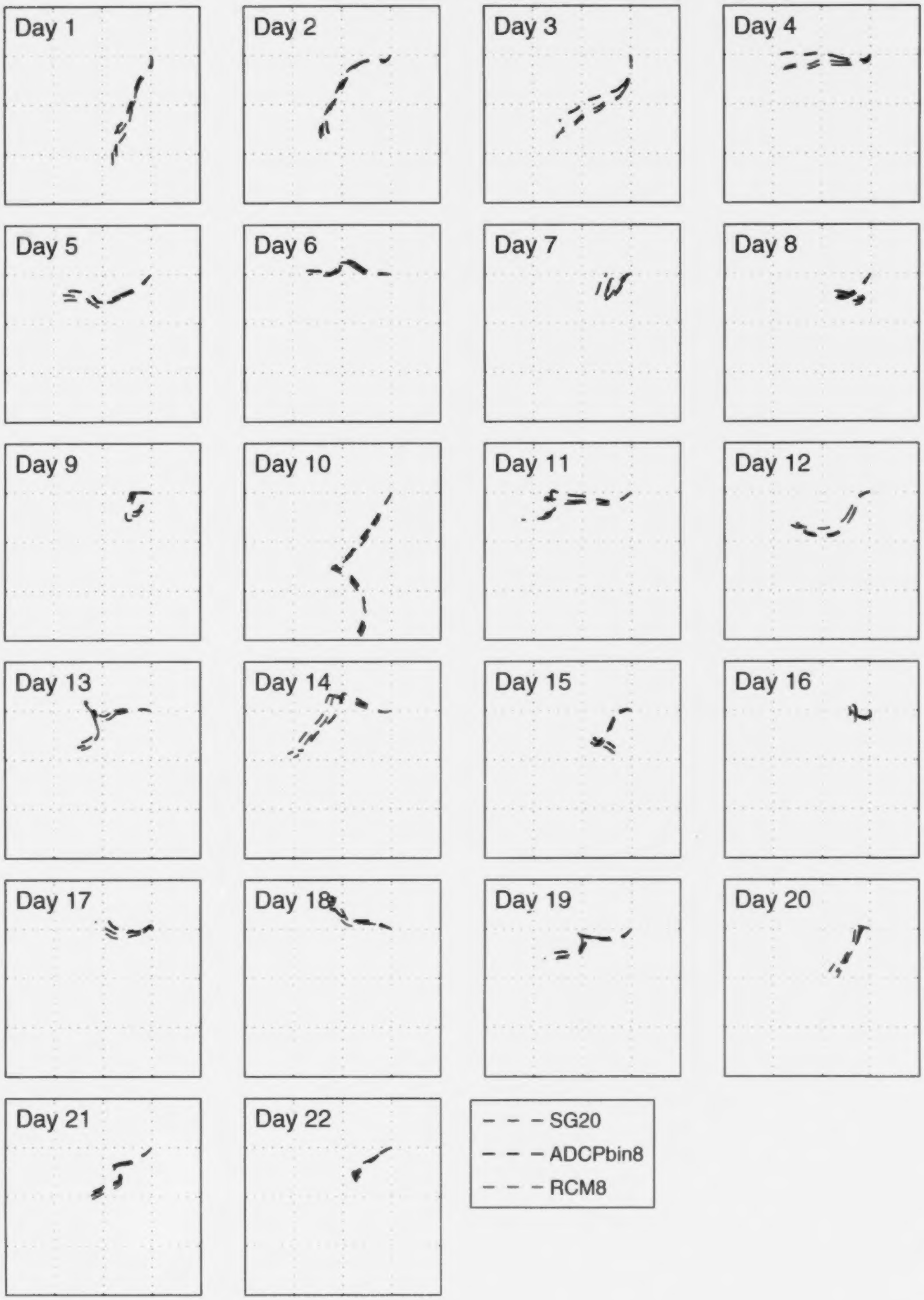

Figure C2: One-day progressive vector diagrams for the period of 12 May to 3 June 2008. Plots include the three current meters in Group 2 at the bottom of the mooring.

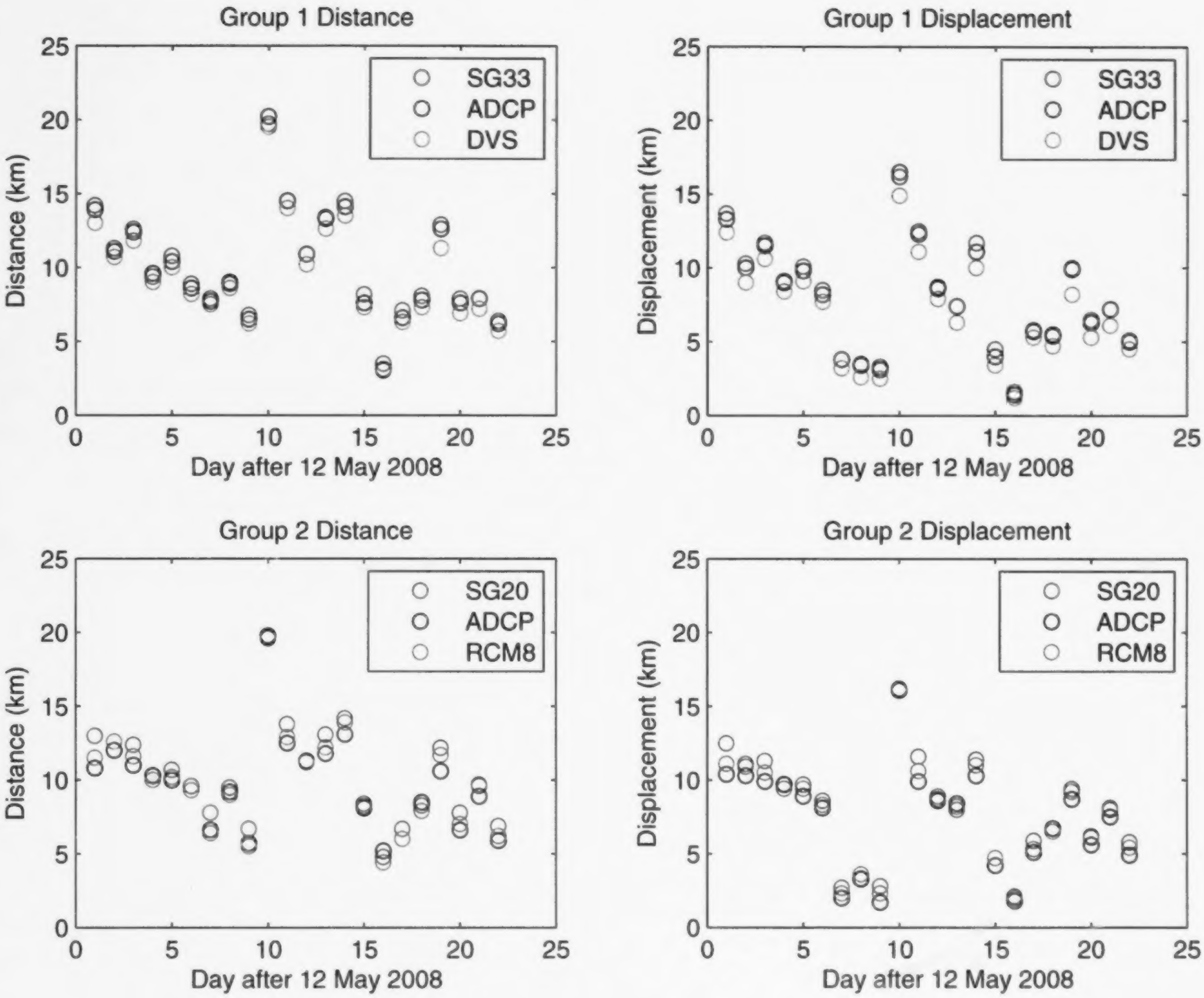

Figure C3: Daily distance and displacement totals from the instruments in Groups 1 and 2. The "Distance" is the path integral (or the gross distance traveled) the "Displacement" is the distance from starting point (net distance traveled).